THE UNIVERSITY OF ALBERTA

THE MESO-SCALE CIRCULATION INDUCED BY THE CITY OF EDMONTON, ALBERTA

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled " The Meso-scale Circulation Induced by the City of Edmonton, Alberta ", submitted by Jay Earl Campbell in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The complex problem of urban induced circulation is explored in this study. The data from four, 3 meter towers around the periphery of the city of Edmonton, Alberta, are analysed.

It is assumed that the wind character at each of the four sites is composed of a mean wind and a perturbation. When the mean wind is vectorially subtracted from the measured wind, the resulting perturbation shows a flow directed towards the heat island centre. Employing the methods suggested by Bellamy (1949), net horizontal convergence is measured and a counterclockwise rotation of the vertical component of the vorticity is indicated, upwind of the city centre.

Five of the experiments conducted during the summer and early fall of 1971 are reported in detail. Each of the five experiments represents a situation which is different, yet typical of the synoptic conditions needed for the induced flow. The mean winds are of varying strength ranging from near 1 m sec^{-1} to near 3 m sec^{-1}. The lowest layers of the atmosphere are stable in all cases over the rural areas at night. The urban temperature profiles for the five experiments vary from near neutral to very stable.

The reports of each of the five experiments also include hourly maps of horizontal wind and temperature profiles.

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CHAPTER I

BACKGROUND TO THE EXPERIMENTS

1.1 Introduction

Cities have often been described as analogous to islands, not because of some aesthetic similarity between the city and a tropical island paradise, but because of the geological and morphological similarity between the intrusion of a city on the landscape and the intrusion of an island on the seascape. A meteorological comparison of the surface temperature of the city and the surrounding countryside led to the continuance of the analogy by referring to the warmer city as an "urban heat island". The surface temperature pattern associated with the heat island is a function of the urban terrain. The temperature differences between areas of high building density and open parkland are significant and are due to the radiative and thermal properties of concrete and asphalt structures and foliated regions. On the average the maximum temperatures are found within the central, core regions of the city. The temperature decreases away from this region (Summers, 1965) to a minimum temperature in the surrounding suburban or agricultural regions.

Although the existence of such an urban meso-climate has been known for close to a century surprisingly few studies have been conducted on the unique heat island structure for a given city. One of these few cities is Edmonton, Alberta where the general isotherm pattern has been analysed by Daniels (1965). The annual and diurnal cycle of the intensity, and the vertical profile of the heat island has been recently described by Hage (1972).

The familiar sea-breeze refers to a local wind on the shores of seas and large lakes, resulting from the influence of the temperature difference between the land and the water. The urban-island analogy can then be carried yet one step further. Although the urban heat island is not as abrupt a perturbation as

the classical sea island, it still may produce a solenoidal circulation similar to the sea-breeze circulation. This flow would be characterized by cooler country air flowing towards the urban centre.

Case documentation of this phenomenon is, however, relatively rare. Chandler (1960, 1965) has extensively investigated the cities of London and Leicester and has described with the aid of drifting soap bubbles, cool breezes varying in speed up to 2.3 meters per second (m sec^{-1}) on stable summer and autumn nights. Pooler (1963) has observed this same type of air movement in Louisville, Kentucky, under similar atmospheric conditions.

Okita (1960, 1965) using the novel techniques of analysing the thickness of rime ice deposits and directions of smoke plumes described such a convergent flow in Asahikawa, Japan. Findlay and Hirt (1969) investigated the meso-scale flow pattern in Toronto, Canada. The flow was associated with the urban heat island. However the proximity of Lake Ontario and the large temperature gradient at the boundary of the lake and the city would indicate that the lake breeze also played an important role in the meso-scale meteorology of this city. Separation of the components of the circulation due to the lake breeze and the heat island was not possible. The total effect was to produce an inflow to the city with speeds as large as 1.7 m sec^{-1}.

There have been several attempts to model the classical heat island circulation. Among the more noteworthy were the early models by Estoque and Bhumralkar (1969). A rather strong wind system was indicated due likely to the very large temperature gradient at the boundary between the heated and unheated regions. Delage and Taylor (1970) modifying Estoques classical sea-breeze models[1] analysed the vertical wind and temperature profiles under

1. One of the most important changes made by Delage and Taylor to Estoques model was the modification of the boundary conditions.

several initial conditions. Included in this analysis were the profiles induced through differential nocturnal cooling. The formation of an advective inversion was one of the most significant conclusions of the paper. In a recent paper Vukovich (1971) used a simple linear model to compute the wind system. The surface heating distribution was more characteristic of the urban heat island than in previous attempts where the urban area was of uniform temperature and the temperature gradient at the boundary was infinitely large. The Vukovich (1971) model described the flow for two stability categories; a stable boundary layer and a relatively unstable boundary layer. Each of these stability categories was described for a no-mean-wind case and for the case when a mean wind existed. Olfe and Lee (1971) in a very important refinement of these previous models extended the analysis to the third dimension. The subsequent analysis of the three dimensional wind and temperature profiles represents the latest advancements in the modeling of the heat island induced circulation.

The study of such an induced circulation is of great interest in meteorology. The solenoidal circulation is a result of the complex interaction of not only the thermic nonhomogeneity of the underlying surface but also of the urban-rural difference in roughness, moisture, and pollution. A detailed knowledge of the relationships of these variables is a prerequisite to the improvement of urban diffusion models. The effect of these variables on the inflow and the subsequent effect of the induced flow on the pollution intensities, visibilities, and the spatial and temporal distribution of temperature and humidity all will aid in the understanding of practical urban ventilation problems.

In the present study the horizontal convergence of the airflow upwind of the city centre, induced by the urban heat island of the city of Edmonton, Alberta is documented. During the summer and early fall of 1971, seven experiments were conducted under light regional winds. The lowest levels of the atmosphere were stable

over the rural areas during all of the experiments. The urban temperature profiles varied from near neutral to slight inversions. Each experiment consisted of the continuous measurement of wind speed and direction simultaneously at four sites near the built-up limits of Edmonton. An analysis of the wind directions and speed, and a subsequent calculation of the net horizontal divergence and vorticity using Bellamys' (1949) method of calculation shows the effect of the urban heat island on these parameters. On one occasion a very strong, pulsating, urban induced country wind was well documented.

1.2 Theoretical Treatment

The urban heat island, though not as abrupt a perturbation as the classical heat island, which is discontinuous at the boundary, should produce a solenoidal circulation similar to the sea-breeze circulation. The basic principle under which the urban heat island circulation would be produced is the same as the sea-breeze circulation; only the character of the forcing function would be different. The thermic nonhomogeneity between the urban area and the rural area would set up a mass and thermal contrast. Potential energy would then be converted into kinetic energy as the warm air would rise over the urban centre and cold air would sink in the rural areas. A thermal low and horizontal convergence would characterize the heated area and horizontal divergence would be found in the cooling zone similar to that found by Stern and Malkus (1953) with the classical heat island. The differential heating and the change of potential energy to kinetic energy would also produce a gravity wave train which would propagate upwind and downwind and produce oscillations on the basic solenoidal circulation (Geisler and Bretherton 1969; Vukovich 1971). In describing the circulation there are two stability categories (after Vukovich 1971) which need to be considered: (1) a stable boundary layer and (2) a comparatively unstable boundary layer. Each of these stability categories would then be described for a no-mean-wind case and for the case when a mean wind

existed.

1.2a No Mean Wind

Initially, a highly simplified model of the urban heat island is assumed. The heating and therefore the motion is constrained to vary in the x and z-coordinate plane only, such as was suggested by Gold (1956). See Figure 1. This defines an infinitely long heat mound along the y-coordinate. The time and space scales associated with the urban heat island circulation are small and so the Coriolis parameter can be neglected. Neglecting this force results in the solenoidal flow remaining in the initial x and z-coordinate plane so that the plane of the flow is not a function of time. Under the above constraints, the linearized perturbation equations of motion for the case of no-mean-wind were given by Vukovich (1971) in the form

$$\frac{\partial u'}{\partial t} + K_f\, u' = -\frac{1}{\bar{\rho}}\frac{\partial p'}{\partial x} \tag{1.1}$$

$$\frac{\partial w'}{\partial t} + K_f\, w' = -\frac{1}{\bar{\rho}}\frac{\partial p'}{\partial z} - \frac{\rho'}{\bar{\rho}}\, g \tag{1.2}$$

where u' is the perturbation x-wind component

t is time

p' is the perturbation pressure

$\bar{\rho}$ is the average density

w' is the perturbation vertical velocity

g is gravity

K_f is the coefficient of friction

and ρ' is the perturbation density.

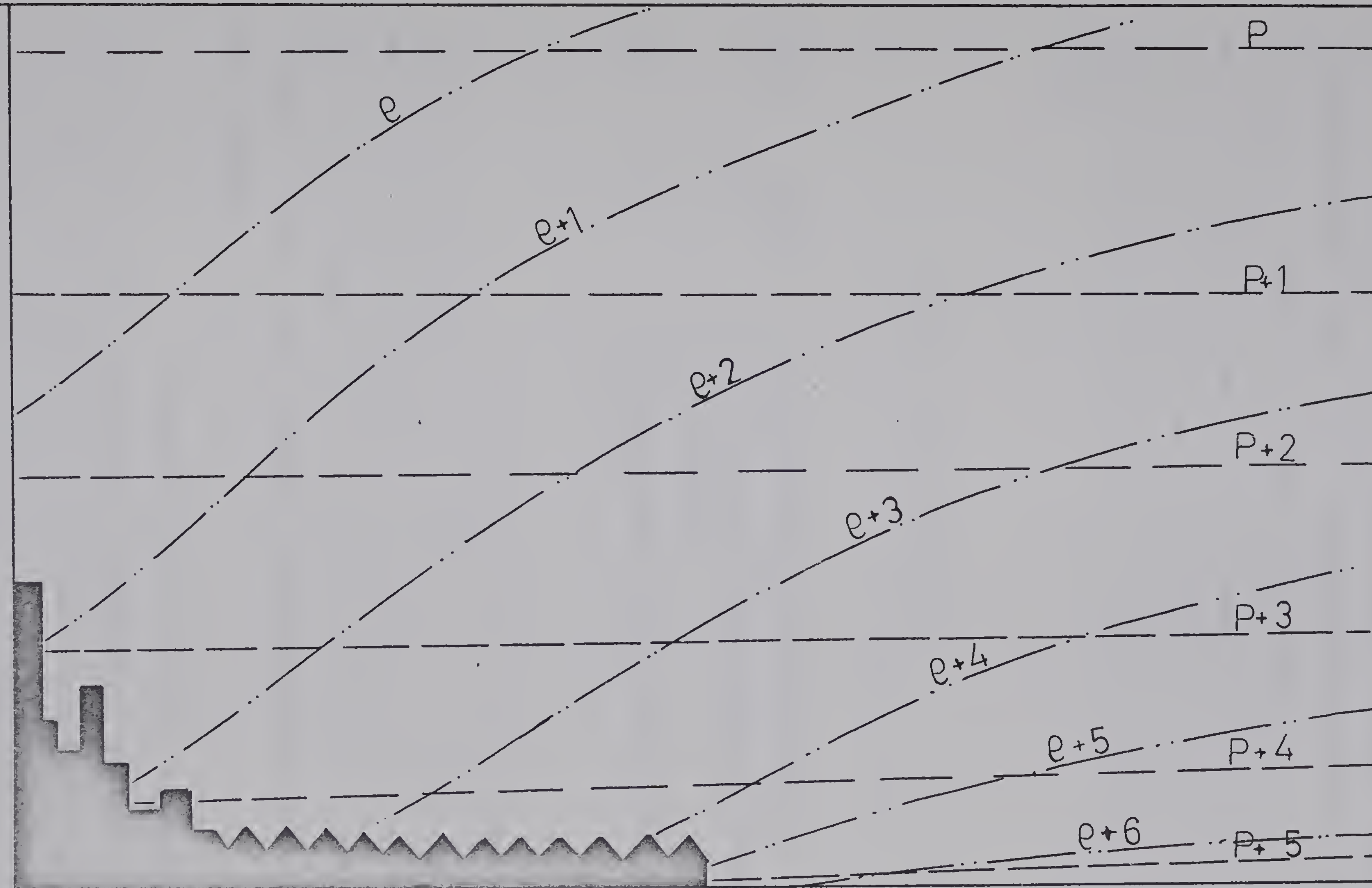

Figure 1. Isobars and isosteres in a vertical cross-section through the atmosphere near a city with a strong heat island.

To describe a heating function where the rural areas are cooling at a more rapid rate than the urban areas (such as would be the case in the evening when there is no mean wind and the skies are clear) the heat energy added per unit time per unit mass, Q, could be assumed to be composed of two parts: (1) an average heating rate, $\bar{Q}$, ($\bar{Q}$ is not a function of x or t) and (2) a superimposed heating perturbation Q'. Vukovich assumed the heating rate to be

$$Q = (\bar{Q} + Q'\cos kx)H(h-z) \tag{1.3}$$

where	$H(h-z)$	is the Heaviside unit function
	k	is the spatial wave number for the heat perturbation
and	h	is the height above ground that the heating persists.

In solving for both the horizontal and vertical profiles of wind under the assumption that there is no mean wind, Vukovich (1971) considered two stability cases for the lowest boundary layer ($0 \leq z \leq h$). These were the isothermal layer in one case ($\partial T/\partial z = 0$) and a near neutral stratification in the other ($\partial T/\partial z = -8.0°C/km$).

In both cases a two cell circulation system was derived. Low level horizontal convergence, upward vertical motions, and upper level horizontal divergence were characteristics of the motion field over the city. Low level horizontal divergence, downward vertical motions, and upper level horizontal convergence were found in the motion field in the surrounding areas.

Differences in the two stability cases were quite evident, particularly in the horizontal wind speed analysis. Horizontal wind speeds were greater for the stable case. Maximum low

level wind for the stable case was approximately 0.8 m sec^{-1} as opposed to the 0.3 m sec^{-1} found in the near neutral case. The vertical compression associated with the stable case requires larger horizontal velocities to maintain the nondivergent state assumed. On the other hand, the vertical velocities were larger in the near neutral case (5.7 cm sec^{-1}) than those found in the stable case (5.0 cm sec^{-1}) over the centre of the urban area.

1.2b Circulation With a Mean Wind Added

The equations governing the motion in the case where there is a mean wind added are derived by Vukovich (1971) in nearly the same way that the equations were derived in the preceding section. The exceptions are (1) that the mean wind $\bar{U}$ is added and (2) that friction is neglected. Vukovich (1971) did not elaborate on the exclusion of friction with a mean wind added. Indeed, as noted by Angell et al. (1971), the city frictional effects neglected here, would also be important, particularly under near neutral conditions.

It is convenient to assume that $\bar{U}$ is independent of x, z, and t. The equations of motion were given by Vukovich (1971) in the form

$$\left(\frac{\partial}{\partial t} + \bar{U}\frac{\partial}{\partial x}\right) u' = -\frac{1}{\bar{\rho}}\frac{\partial p'}{\partial x} \qquad (1.4)$$

and

$$\left(\frac{\partial}{\partial t} + \bar{U}\frac{\partial}{\partial x}\right) w' = -\frac{1}{\bar{\rho}}\frac{\partial p'}{\partial z} - g\frac{\rho'}{\bar{\rho}} \qquad (1.5)$$

1.2b (1) Stable Case

The two cell circulation is still evident in the horizontal velocity field when there is a mean wind and the lowest layer of the atmosphere is stable. The difference between this case and the case of no mean wind is that the entire system is displaced downwind of the heat source. The vertical extent of the circulation increased by about 250 meters over the height in the no-mean-wind case. In the no-mean-wind case the region of maximum vertical velocity was found over the centre of the heat island. The effect of the mean wind was to move this region downwind a distance proportional to the strength of the mean wind. The horizontal extent of the solenoidal cell was nearly unchanged. This means that when the cell was moved downwind, the part of the city upwind of the city centre experienced downward vertical velocities. The speed of the circulation was influenced by the mean wind speed, the gravity wave speed, and the heating distribution. The quasi-equilibrium state of the system was brought about by a balance between the acceleration produced by the heating distribution tending to bring the system back to the heat source and the mean wind and gravity wave effects which transport heat and momentum downwind (Vukovich, 1971).

1.2b (2) Near Neutral Stability

The intensity and vertical extent of the horizontal circulation in this case was nearly equal to that found in the analogous case where there was no mean wind, but the system was displaced downwind. The vertical velocity on the other hand was more intense and the area of maximum vertical velocity was displaced downwind. As in the stable case the part of the city upwind of the city centre might be characterized by downward vertical motions. The amount of displacement was proportional to the mean flow. This displacement was found by Vukovich (1971) to be 11 km with a mean flow of 10 m sec^{-1} and 3 km with a wind of 3 m sec^{-1}.

1.3 The Three Dimensional Solution

The three dimensional perturbation solution for the flow over a heat island can be obtained by superimposing the two-dimensional solutions at varying angles to the mean flow direction. Olfe and Lee (1971) used this approach with circular isotherms over the city. They suggest that other isotherm shapes could be considered by the introduction of a weighting function.

The effect of changing the two dimensional solution to a three dimensional one, was the decrease of the vertical extent of the circulation and the decay in the three dimensional perturbation in the direction perpendicular to the mean flow.

To this point the Coriolis and viscous effects have been neglected. It was assumed in the two dimensional solution that these effects were negligible. Olfe and Lee (1971) noted, however, that in the three dimensional solution the Coriolis force damps the velocity oscillations. As the Rossby number tends to zero the velocity perturbations tend to zero and in the limiting case this results in the pure conduction solution for the temperature perturbation. In an example using data from New York City (the Rossby number was approximately 4.6), Olfe and Lee (1971) showed that the magnitude of the negative temperature perturbation was not appreciably reduced by the Coriolis force. The y component perturbation estimated about a 6° anticyclonic turning at the New York heat island centre.

CHAPTER II

THE CITY OF EDMONTON ALBERTA

2.1 The Physical Description

The city of Edmonton, Alberta (pop. 436,000 in 1971), the capital of the province of Alberta, is located in the central region of the province at 53' 35" North, and 113' 30" West, with an average elevation of 660 meters (2200 ft.) above mean sea level. The surrounding area was covered by a continental glacier with a maximum thickness of 1.6 km (1 mile) during the Wisconsin glacial period. The retreat of the glacier was due largely to melting. The natural drainage of central Alberta is northeasterly and as the glacier retreated in that direction, melt waters impounded in front of the glacier resulting in marginal lakes. One such lake was Lake Edmonton which when drained by the North Saskatchewan River, left a large area with flat lacustrine deposits upon which the city is built. The relatively flat plain of the city's area is interrupted only by the often steep banks of the North Saskatchewan River Valley. The river enters the city area from the southwest and meanders diagonally through the city leaving northeast of the city centre. Within the city the valley seldom exceeds 1.6 km (1 mile) in width and on the average the walls are 60 meters (200 ft.) high, being in the form of cliffs that in places are steep compared to a more gentle slope towards the city centre. There are several open areas within the 150 square kilometers of the city including many parks, play areas, the Industrial Airport, railway yards, and sports facilities. The river valley is generally treed parkland except east of the Low Level Bridge which is residential, and the low flood plain northeast of the 105th Street Bridge which contains the City Power Plant and several apartment buildings. The main business district is of moderate size extending from the Canadian National (CN) Railway lines

south to the river and from 109th Street eastward to 97th Street. The buildings in this area are at least two stories in height and range upwards to the 44 stories of the Alberta Government Telephones building. The building density in this area can be described as very high. The only open area in this region of the city (except for the streets) is Winston Churchill Square, a small, one square block open area near the centre of the city.

A smaller business district is situated on the south side of the river in the vicinity of 82nd Avenue and 104th Street. Here the buildings are two to four stories tall with a medium horizontal density. The rest of the city, surrounding this central area, is low density residential area interspersed with a few commercial areas. Heavy industries are confined almost entirely to the eastern outskirts near the river valley.

The built-up limits of the city of Edmonton and the topographic features of the area are shown in Figure 2.

2.2 The Heat Island of the City of Edmonton

It is well known that urban areas generally have higher temperatures than their surrounding rural areas. Although the existence of the heat island has been known for close to a century, very few detailed analysis of its oscillations have been carried out. Edmonton is one of the few cities where such studies have been conducted.

The horizontal isotherm structure for the heat island of Edmonton has been investigated by Daniels (1965), using auto traverse data. The isotherm pattern showed a temperature excess

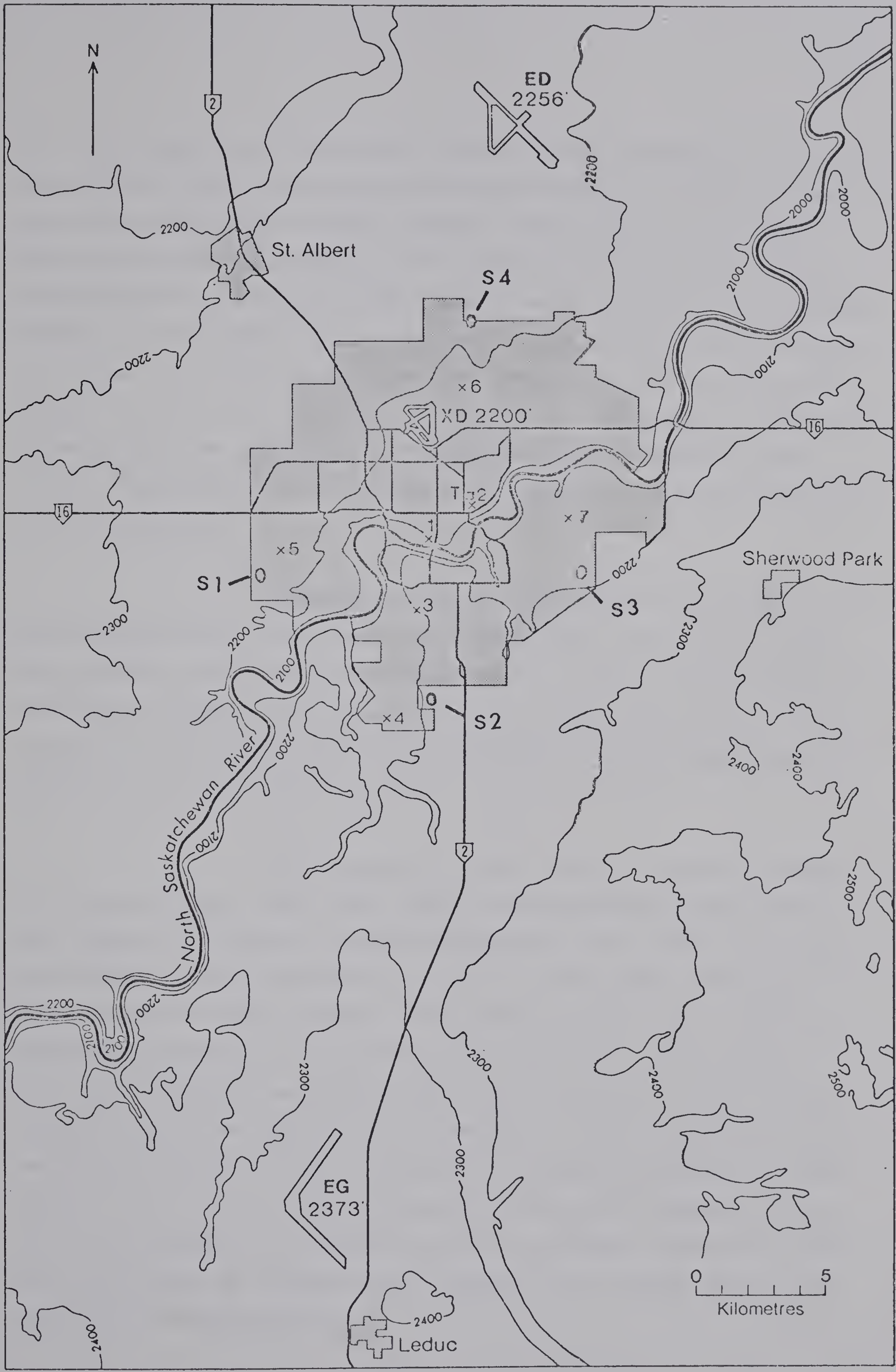

Figure 2. The city of Edmonton, Alberta showing thermograph stations and tower sites.

over the central core area with a weaker second maximum on the south side of the river in the vicinity of the University of Alberta campus and the adjacent business complex. The temperature decreased linearly towards the boundary of the city with the exception that the gradient was stronger at two transition boundaries; (1) the transition from the high density core area to the predominantly residential area and (2) the transition from suburbs to rural countryside. Daniels (1965) also found that the effect of a mean wind on the isotherm pattern was to extend the isotherms downwind from the heat source. The amount of the extension was dependent upon the magnitude of the mean wind.

Although no similar study has been conducted for the Edmonton heat island, Mey (1933) found that the critical speed (the speed at which the heat island would no longer be discernable) for Bremen, Germany was 8 m sec^{-1}. At the time of the study the population of Bremen was approximately 400,000. An approximation of the critical speed for Edmonton would then be 8 m sec^{-1}.

The urban heat island exhibits a marked diurnal oscillation (Hage, 1972). The largest contrast between the central core regions of the city and the suburban and rural area is at night about three to four hours after sunset in both summer and winter. There is little or no contrast during the daylight hours. Vertical temperature gradients in the lowest 100 meters over the central urban core reached a maximum shortly after midnight (local time) on intense heat island nights in all seasons. A stable stratification persisted through all hours of the day following strong heat island nights in the city in winter. Temporary inversion breakdowns occurred in the presence of strong vertical wind shears. Inversion breakdowns affecting the surface level appeared to be patchy and of rather small horizontal scale.

The annual cycle of heat island intensities was of small amplitude. Although no rigorous tests of significance were available, Hage (1972) found that there were small peaks in January-February and in June. These apparent peaks coincided with the months of maximum artificial heating and of maximum solar heating, respectively.

2.3 The Macro-climate of Central Alberta

A particular urban climate is largely dictated by the macro-climate of the region where the city is located. The climate of central Alberta is continental in nature. The winter months see outbreaks of Polar air giving sharp cold spells. With a steady flow of very cold air crossing the frozen polar seas into the continental heart of the Great Plains and confined east of the barrier of the Rocky Mountains, cold spells may last for several weeks. On the other hand, a milder westerly or southwesterly flow may push the entrenched cold air off to the east.

The summer months see a predominating flow from the west. The Maritime Polar air from the Gulf of Alaska dries itself as it crosses the Rockies and flows down the eastern slopes. This air is dry and relatively cool compared to the Maritime Tropical air which invades more southerly parts of the continent. The upper flow is often subjected to very cool thermal troughs, resulting in unstable conditions of the atmosphere, particularly through the area to the east of the Rockies, between Edmonton and Calgary.

2.4 The Climate of Edmonton

Edmonton is the most northerly city of its size in Canada. Its protected position in the lee of the Rocky Mountains gives an annual average precipitation of only 47.35 cm. However, 65% of this falls in the late spring and summer.

The climate could be described as a cold temperate climate but it is not as severe as might be expected in a continental climate at 53° North. The chinooks which modify the long winter just to the east of the Rockies do not usually reach as far east as Edmonton. However, the modifying influence does extend to Edmonton for brief spells nearly every winter.

The summers in Edmonton are usually pleasant. Moist, tropical air which brings heat waves to most of the interior of the continent, never reaches as far north as Edmonton. Maritime Pacific air, which comes from the west, is dried by the passage over the Rockies. Consequently, relative humidity averages are lower in Edmonton than in most other places on the western plains.

In Appendix A there is a comparison of the summer months of June through September inclusive, between the climatic average and the summer during which the experiments took place, 1971. The data are from the Edmonton Industrial Airport[2] and are compared by month in Tables A-1 to A-8.

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2. The wind speed and direction from the Industrial Airport were measured by a U2A anemometer. A contact cup type 45B anemometer was taken out of service in January 1970. The data in the climatological record were obtained with the 45B equipment while the comparison was with U2A equipment. The measuring level was 17.4 meters above the ground and approximately 9.1 meters above the roof of the administration building. No change was made in the sensing level when the anemometer type was changed.

CHAPTER III

THE DATA AND THEIR COLLECTION

3.1 Measurement Problems

In light wind situations, the starting speeds of standard anemometers and vanes are too high to permit a useful analysis of the flow. Indeed, under these conditions the surrounding reporting stations, using conventional instrumentation, often reported "calm" when in fact light flows were present.

Two ingenious methods of deliniating the characteristics of the light country wind have been described by Okita (1960, 1965). On winter nights when there was a super-cooled fog in the city of Asahikawa, Japan, Okita (1960) noted that rime ice formed on the upwind side of the branches of trees, and that the thickness of the ice was an index of the local wind speed, time integrated overnight. Observations obtained shortly after sunrise permitted an estimate to be made of the meso-scale flow patterns. In a subsequent study on the same city, Okita (1965) estimated the wind directions by observing the smoke plumes from a number of chimneys.

Another method that has been used on special occasions was the tracking of constant-level balloons or tetroons (Hass et al., 1967). Chandler (1960, 1965) used drifting soap bubbles in an attempt to measure the country wind.

In the present study if the attempt to measure the flow was to be made through Lagrangian methods such as the methods which have just been described, then the main difficulty would have been in the tracking of the particles (balloons, soap bubbles, etc.). On the other hand, if the attempt were to be made

through Eulerian methods then the main problems would be in choosing sites which were representative of the city as a whole and obtaining equipment which was sensitive enough to measure such a very light flow. It was decided that these latter difficulties would be easier to overcome than the former.

As was suggested by Munn (1968) an inventory was made of the existing meso-scale data network. It was found that the temperature data network in Edmonton was acceptable with both the horizontal and vertical profiles available. On the other hand, the wind data network was less than adequate for this type of study. Firstly the anemometers in use at the three airports within the immediate area of the city of Edmonton were of conventional design. As has been suggested before, the starting speed of such equipment is too high for the light winds which it was hoped to measure. Also the nearly linear north to south alignment of the three airports was less than adequate for the peripheral picture it was felt necessary to measure.

With these restrictions in mind, it was decided that the problem of documenting an urban-induced circulation could best be accomplished through a measurement of wind speed and direction at each of four sites on the periphery of the built-up area of the city. Wind sensing equipment of "conventional" design was used with the exception that instrumentation was found or built such that a very low starting speed was achieved.

3.2 The RIMCO Sensitive (Low Torque) 3 1/4" Cup Anemometer

The type of anemometer chosen was the RIMCO-CSIRO[3] Sensitive Cup Impulse Anemometer R/ASI. This anemometer had a starting speed of no more than 10 centimeters per second (cm sec^{-1}) wind speed and had a nearly linear calibration down to this speed. This made the instrument particularly suitable for a study involving low wind speeds.

Wind tunnel calibration of a number of these instruments, by the manufacturer, showed results to be within ±1% of each other through the operation range and linearity within ±1 1/2%. They had been operated at wind speeds up to 25 m sec^{-1} without damage and in temperatures up to ±60°C.

TABLE 1. The anemometers used at each of the four experimental sites.

Anemometer No.	Site Location	Calibration Certificate No.	Date of Calibration
ASI 4070	spare	133/(5)/70	12/8/1970
ASI 4170	1	133/(5)/70	13/8/1970
ASI 4270	2	133/(5)/70	13/8/1970
ASI 4370	3	133/(5)/70	12/8/1970
ASI 4470	4	133/(5)/70	14/8/1970

Each anemometer was provided with a pulse generator and a power amplifier, mounted in the base of the anemometer. The instrument was powered by a 12 volt D.C. dry cell. The current consumption was measured at 120 milliamps when connected to a 200 ohm post office message recorder (counter). A square wave pulse with

3. CSIRO - Commonwealth Scientific and Industrial Research Organization Aspendale, Victoria, Australia.

equal mark to space ratio operated the counter. One pulse was generated for each rotation of the cups. A wind speed of 12 m sec^{-1} gave 400 pulses per minute.

A 6-digit counter capable of 400 counts per minute was used to record the number of cup rotations.

3.3 The Vane

The vane used in the experiments was similar in shape to conventional meteorological vanes. Essentially the vane was an airfoil mounted unsymmetrically about a vertical axis on which it was free to turn. Certain modifications were made to the conventional design in an attempt to achieve a low starting speed.

To make the vane light, the superstructure was made of balsa wood. A silkspan covering completed the vane which was then mounted on a birch dowling shaft. The four vanes were matched as closely as possible, not only to the airfoil shape but also to weight. The average weight of the four vanes was 56.5 grams with the extreme weights giving a range of 3 grams.

With such low mass the vane had but small inertial forces. This made the vane very responsive even to gentle breezes. Because the momentum of the vane was also quite small very little overshoot was experienced

Because the purpose of the vane was to measure a mean direction over a period of time which could be very long, the span to cord ratio of the vane was designed to be one to one with each length being 30 cm. The maximum width of the airfoil was 4.9 cm.

The distance from the leading edge of the vane to the pivot point was 15.5 cm. This distance was determined experimentally so that the greatest torque could be achieved with the counterbalance limited to a reasonable size.

The vane drove a Helipot continuous-wound potentiometer, whose resistance varied from 0 to 1K ohms. The four potentiometers were matched in response to ±1%. There was a certain amount of frictional resistance to the vane rotation in the potentiometer. This was, however, apparently very small.

3.4 The Recording of the Wind Character

The wind speed was determined by changing the number of revolutions of the cups, as measured by the counter, into counts per minute. The calibration certificates provided with each anemometer were then used to change the counts per minute into a wind velocity in meters per second. It was possible to read accurately the velocity from the graph to the nearest centimeter per second. Observations of the counter were made every 5, 15, or 30 minutes on various experimental runs. The observation frequency was determined prior to each experiment so that the count observations were made simultaneously at each of the four towers.

Observer error could arise in the computation of the wind speed. This type of error would arise if the observations were not made simultaneously. Because the observers were asked to report the time of the observation to the nearest minute the maximum time error that would be possible would be ±30 seconds. If the wind were blowing at 1.5 m sec^{-1} (an average value of the observations over the whole of the experiments) the magnitude of the error in the reported wind speed would be 5.0 cm sec^{-1} if the observations were being made every 15 minutes, and 2.5 cm sec^{-1} if the observations

were being made every half hour.

The wind direction was sampled every second by means of a digital recorder[4]. The deflection of the stylus of the recorder was recorded through the impinging action of the stylus against pressure sensitive paper. From zero to full deflection of the stylus was achieved through one revolution of the potentiometer and represented 360° of wind direction. The stylus wrote along its length rather than at its point. Because the recordings were rectilinear, the reading of the charts was facilitated.

The writing speed of the recorder was one sample per second and the chart speed through the recorder was 1 inch per 5 minutes.

3.5 The Towers

With the vane and the anemometer being as sensitive as they were to inclement weather[5] it was decided that the instrumentation would be set up only for the duration of the experiment. This necessitated the design of a tower which could be readily assembled and quickly taken down. Great care had to be taken in the location of the sensing equipment on the tower. For example, in an attempt to measure the urban-induced circulation, Pooler (1963) analysed the winds at a height of 157 meters above the ground as obtained

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4. Rustrak D.C. Recorder (Model 2146). The four used in the experiments were numbers N31246, N31251, N31252, and N31253.

5. The vane and the anemometer could withstand wind speeds up to 25 meters per second. Both could also withstand rain; the vane would likely become soaked and the readings suspect while it was wet but it would eventually dry. However a combination of strong wind and rain, such as occurs in a thunderstorm, would likely destroy the vane. Certainly hail, which has a high probability of occurrence in Edmonton in the summer, would ruin both the vane and the anemometer.

from a television tower in Louisville, Kentucky. There was a noticeable wind-shadow effect when the flow was from the tower towards the anemometer.

With these concerns and limitations in mind four " T " shaped towers were built. The sensing level was 3 meters. The anemometer and the vane were situated at either end of the horizontal boom such that they were 2 meters apart. Four guy lines and turnbuckles were used to keep the tower vertical (±1°). The recording instruments and power supply[6] were conveniently located on the tower.

3.6 The Calibration and Operation of the Instruments

Because the equipment was portable, great care had to be taken in setting up the tower not only to ensure that it was vertical but also to ensure correct orientation of the tower for accurate determination of the wind direction.

Prior to the experiment, the recorders were checked to make sure that there was one sample every second and that the speed of the chart paper through the recorder was exactly 1 inch every 5 minutes. The power supplies were checked for correct voltage. The anemometers were tested to see that there was one impulse per revolution of the cups and the potentiometers were tested to ensure that one revolution of the vane would give full scale deflection of the recorder stylus.

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6. 12 volt D.C. dry cell. Everready battery No. 732 NEDA 926.

During the run of each experiment several checks were made to ensure accurate recordings of the wind direction. At least twice at each tower the exact direction of the flow was determined using a Silva System compass and the simultaneous Rustrack deflection was marked on the recording paper. The full scale deflection point was also rechecked at the conclusion of each experiment.

3.7 Other Sources of Data

The surface temperature data were obtained from seven shielded thermographs[7] at various locations within the city (the numbered locations in Figure 2), from the Edmonton International Airport (EG) about 26 km south southwest of the city centre, from the Edmonton Industrial Airport (XD) about 3 km northwest of the city centre, and from Canadian Forces Base Namao (ED) about 16 km north-northeast of the city centre. The airport temperatures were measured with mercury thermometers in ventilated Stevenson screens. Vertical temperature profiles were obtained from shielded, aspirated electrical resistance thermometers mounted on booms at 17 meters and 112 meters extending from the north face of the CN Tower building in the centre of the city (T in Figure 2) and from the Stony Plain radiosonde station about 41 km due west of the city centre. Conventional hourly airways observations of cloudiness, visibility, wind, precipitation and other elements were available for all three airports shown in Figure 2.

Operation, maintenance, and calibration of the thermographs and CN Tower instruments were performed by Geoscience Research Associates Limited of Edmonton. Airport weather data were supplied by the Atmospheric Environment Service of the Department of the Environment, Canada. The thermographs were mounted on steel

7. Station number 4 (Figure 2) was inoperative during the month of July and was completely shut down in September 1971.

posts at a height of 1.5 meters above grass surfaces. All thermographs were calibrated at a common site prior to installation and this was followed by weekly calibration checks with a portable aspirated psychrometer.

3.8 Siteing Problems

Urban flow during light geostrophic winds is in fact much more complex than the simplified models that were outlined in the theoretical discussion. In the first place the flow is likely to be intermittent. Chandler (1960, 1965) has observed in both London and Leicester, that the outer perimeter of the nocturnal heat island was not only rather sharp but also that it pulsated during the night. A pool of cool air accumulated over the country side, and drifted into the city intermittently when the horizontal temperature gradient exceeded some critical value. The flow of the surface air would likely be down streets and modest slopes to the many ravines and then into the North Saskatchewan River Valley.

Secondly, smaller circulations are induced by parks and other anomalies in the urban complex. The city itself presents many varying characteristic surfaces; the very rough concrete-asphalt core area, the heavily-treed older residential section of Glenora, the almost treeless newer suburban sections to the north, west, and south of the city, the very large open area of the Industrial Airport, and the heavily industrialized eastern portion of the city all present anomalies in the surface thermic pattern of the urban complex. In every case, horizontal temperature gradients may generate local drifts of air. Whiten (1956) and Gold (1956) both speculate that the heat from automobiles in Londons' Oxford Circus is sufficient to produce air exchanges with adjacent parks during smoggy conditions. Schmidt (1963) found local circulations induced

around an industrial area.

A consideration of these governing contingencies, led to a choice of sampling sites which were:

(i) close to the built-up limits of the city

(ii) open and flat

(iii) away from major commercial or industrial areas

and (iv) well removed from the ravines and the river valley.

Because the instrumentation for the sampling was portable, it was also expedient to choose sites which were easily accessible, so that the instruments could be carried close to the sampling site by a truck. Also, because four towers had to be erected and taken down for each experiment it was advantageous to choose sites which were close to major arteries, so that as little time as possible would be spent in this phase of the experiment.

Four such sites were found. Although not completely ideal, the observations from these sites can be said with good confidence to be representative of any flow induced by the urban complex. These sites are marked on Figure 2 as S1, S2, S3, and S4.

3.9 Description of Site 1

Site 1 (S1 in Figure 2) was located west-northwest of the intersection of 165th Street and 88th Avenue in a large open field. The field, as well as the surrounding area, was very flat and free of any major obstructions. The surrounding urban area was predominantly residential. The closest buildings to the site were:

(i) a low, single story nursing home about 150 meters due west of the site

(ii) the seven story Misericordia Hospital 250 meters south-southwest of the site

(iii) a townhouse and high-rise development 300 meters east and extending southeast of the tower location

and (iv) single family, residential area 100 to 150 meters north and northwest of the site.

The tower location was very close to the extreme western edge of the built-up area of the city. Ideally the site would have been due west of the city centre. However, this would have put the site near a major inter-provincial highway. The high density of motels and gas stations in that area made it unacceptable. This site was located on a bearing of 256° from true North and at a distance of about 8 km from the CN Tower, which was considered as the city centre.

3.10 Description of Site 2

Site 2 (S2 in Figure 2) was also located in an open field. The tower location was about 200 meters east of 111th Street and 1 km south of 45th Avenue. The terrain had a gentle downward slope from the west to the east. The site was exceptionally free of major obstructions. A line of small trees 150 meters northeast of the site and some new single family homes under construction 150 meters southeast of the site were the only obstructions within 1 km of the tower. The site was very close to the extreme southern edge of the city.

Ideally the site would have been about 1.5 km farther east so that it would have been due south of the city centre. However that area was virtually inaccessible except by foot (the tower would have had to be carried about 1 km). The terrain in that area was also a little low and wet.

The tower location was 191° from true North and at a distance of 7.5 km from the CN Tower, the city centre.

3.11 Description of Site 3

Site 3 (S3 in Figure 2) was located 15 meters south of 82nd Avenue and about 0.7 km east of 75th Street.

The area in the immediate proximity of the tower was very flat. However, some 75 meters southeast of the site the terrain dropped off sharply to the Sherwood Park Freeway. There were some small trucking warehouses about 0.7 km east of the site and several small wholesale outlets 75 meters north of the tower location.

Ideally the site would have been 3 to 4 km farther east and 3 km farther north. However, this would have put the site in the middle of a row of oil refineries which may have an induced circulation of their own. Schmidt (1963) found such an induced circulation around heavy industries. Because the heavy industries in Edmonton are restricted mainly to the eastern part of the city, compromises had to be made in the location of Site 3. Of the four sites, Site 3 was the closest to the city centre, yet it was virtually on the extreme southeastern edge of the built-up limits of the city.

The site was 123° from true North and at a distance of 4.5 km from the CN Tower, the city centre.

3.12 Description of Site 4

Site 4 (S4 in Figure 2) was located in a very open area 50 meters southeast of the intersection of 132nd Avenue and 97th Street. The site was almost ideally situated, being 1.5° from true North and 6.5 km from the city centre. The surrounding area was flat and open to the North, East and West. The site was very close to the edge of the built-up area of the city. The only adverse complication of this site was the presence of the Northgate Shopping Centre about 100 meters to the southeast of the tower location.

Of the many hours of observations that were taken at this site there was no indication of any effect that was due to the shopping centre. This was ascertained through a comparison of the Tower #4 data with the wind direction data from the nearby Industrial Airport. This led to the conclusion that any error due to the shopping centre was likely very small.

In all four tower locations the area immediately surrounding the site was short cropped grass covered.

CHAPTER IV

THE EXPERIMENTS

4.1 Introduction

Seven experiments were conducted in an attempt to measure the meso-scale circulation induced by the city of Edmonton. In all of the cases the Stony Plain upper air sounding, indicative of the rural vertical temperature profile, showed lapse conditions at 0000 Greenwich Mean Time (00 GMT)[8] prior to the experiment. This profile changed in all cases to a surface inversion by 12 GMT the following morning. The temperature profile over the city varied from night to night. It ranged from near neutral conditions on July 14, 1971 to the inversion of August 19, 1971.

Synoptic winds at standard anemometer levels were light to moderate. The strongest winds were those which were reported during the experiment on the night of September 17, 1971 when the Industrial Airport reported wind speeds up to 8.0 m sec^{-1} during the run of the experiment. Even during this experiment general convergence was measured over the urban area.

The experiment numbers, the dates, and the duration of the seven experiments are given in Table 2.

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8. The local time in Edmonton is Mountain Standard Time (MST). The difference between GMT and MST is 7 hours (i.e. 1700 MST is 0000 GMT and 0500 MST is 1200 GMT).

TABLE 2. The dates and the times of the seven experiments

Experiment No.	Date	Hours (GMT)
1	July 15, 1971	0255 to 0645
2	July 19, 1971	0138 to 0642
3	July 26, 1971	0147 to 0715
4	August 01, 1971	0200 to 0655
5	August 11, 1971	0235 to 0830
6	August 20, 1971	0200 to 0745
7	September 18, 1971	0010 to 0520

4.2 Convergence Calculations

Bellamy (1949) has described a method for the calculation of horizontal divergence using the reported wind observations from any three non-colinear points. Having been given three points of wind observations a convenient assumption for the distribution of the wind field is that the wind is a linear function of the space between the points. Having been given this assumption each wind observation could be treated separately. For example, first it could be considered that the wind at point A (Figure 3) was as observed but that the winds at points B and C were calm. The "partial horizontal divergence", DA, for these conditions could then be calculated. Similarly the "partial horizontal divergence", DB, for the wind at B and calm at A and C, and the value of DC, for the wind at C and calm at A and B could then be calculated. The horizontal divergence D, from the triangular volume was then given as the sum of these partial divergences or

$$D = DA + DB + DC \qquad (4.1)$$

Bellamy used elementary trigonometric evaluations to show that the partial horizontal divergence for, say DA could be obtained from the formula

$$DA = \frac{v}{h_A} \sin (\beta_{BC} - \alpha) \tag{4.2}$$

where α wind direction (true)

β_{BC} azimuth of the opposite side of the triangle

h_A perpendicular distance between point A and the opposite side of the triangle

and v wind velocity.

In this particular study the locations of the sites were known very accurately so the azimuth angles and perpendicular distances were calculated to within $\pm 1°$ and ± 100 meters, respectively. The wind directions were recorded every second, and 30 second averages were read from the recording tape. This allowed 30 minute averages of the wind direction to be calculated quite readily. It was decided to use 30 minute averages of the wind speed and direction in the divergence calculations. Thus the wind velocity was entered into Eq. 4.2 in m sec^{-1} and the perpendicular distance was entered in meters so the dimension of the divergence, DA, was sec^{-1}.

Because there were four towers in use during the experiments it was possible to use four different "Bellamy Triangles" for calculation of the divergence. This was done so that a comparison could be drawn among the results obtained from each of the four triangles. Of particular interest was the comparison between the triangles upwind of the city centre and those downwind.

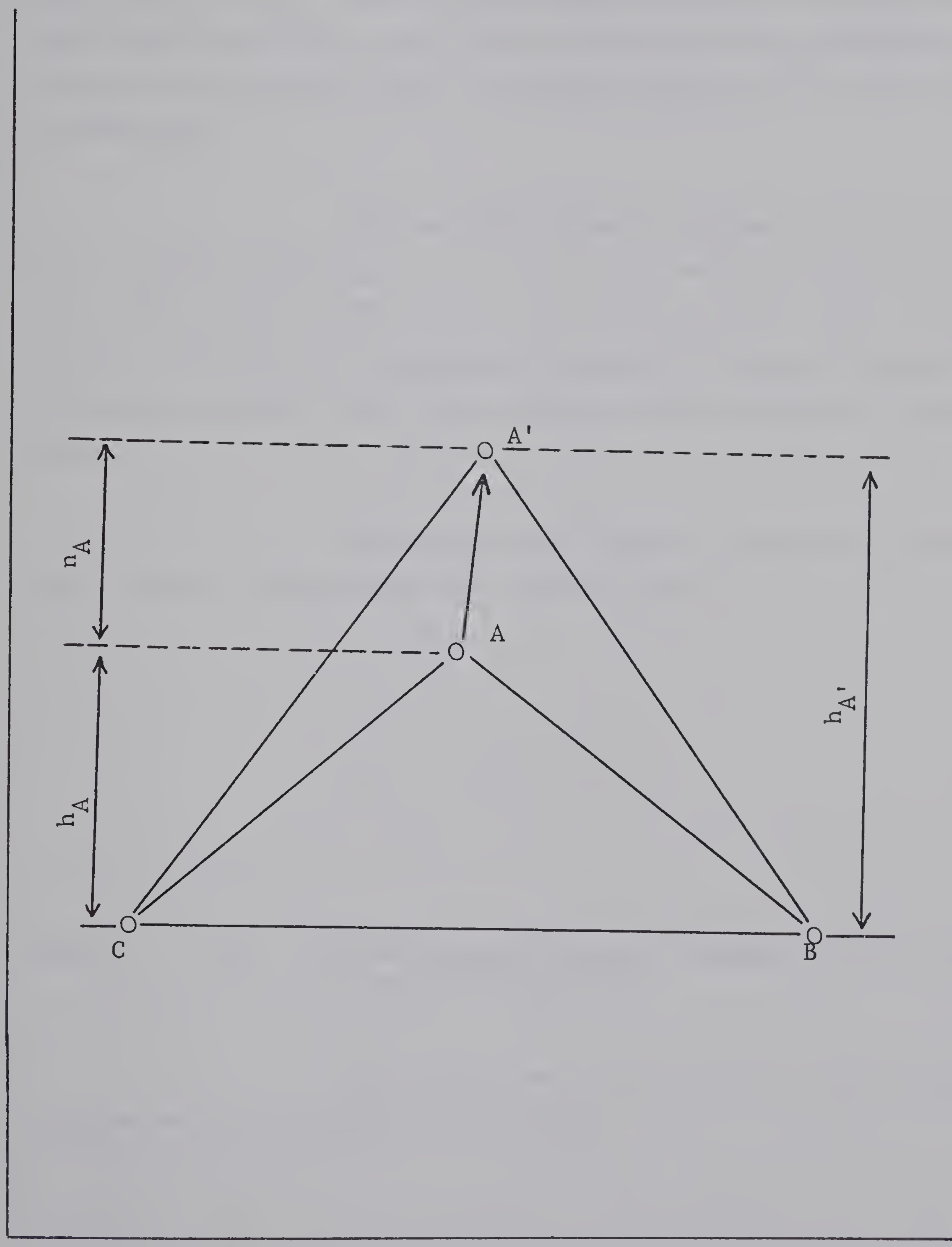

Figure 3. The three non-colinear wind data points (after Bellamy (1949) FIGURE 1).

4.3 Vorticity Calculations

Very early in the analysis of the wind direction data it was noticed that there seemed to be a common turning of the wind over the city. This was indicated not only in the data from the four towers but also in the wind data from the three Edmonton airports. It was decided that a vorticity analysis of the data would be interesting.

The same 1949 paper by Bellamy contained a formula for the calculation of the vertical component of the vorticity. The method of calculation was very similar to that used in the divergence calculations; determine the partial vertical component of vorticity at each of the three points of the triangle and then sum them.

The formula used for the calculation of the partial vertical component of the vorticity was

$$\xi_A = -\frac{V}{h_A} \cos (\beta_{BC} - \alpha) \tag{4.3}$$

where ξ_A is the partial vertical component of the vorticity at point A (Figure 3).

The other values were defined in the previous section on the divergence calculations.

4.4 Sensitivity of the Divergence and Vorticity Calculations to a Systematic Error

Systematic errors were introduced into the observations of wind speed and direction from experiment #5 to see the effect of these errors on the magnitude of the divergence and vorticity calculations. A 10° error was introduced into the data from Tower #1 by subtracting 10° from the observations. Similarly, 10° was added to the directions at Tower #3. The direction data from Towers #2 and #4 were left unchanged. This had the effect of decreasing the perturbations at Towers #1 and #3.

A systematic wind speed error of 20 cm sec^{-1} was introduced by subtracting this wind speed from the data at Tower #2. The magnitude of these errors was larger than a realistic approximation of systematic error in the instruments as will be shown in the next section. The random errors that were possible (i.e. observer error in the wind speed calculations) were not of concern in this analysis. Random errors would tend to be smoothed in the divergence and vorticity calculations because time averages of the order of one-half hour were used.

The systematic error introduced into the wind direction resulted in a standard deviation (S.D.) of 2.5×10^{-5} sec^{-1} in the divergence calculations and 3.6×10^{-5} in the vorticity calculations. The wind speed error resulted in a S.D. of 2.3×10^{-5} sec^{-1} in the divergence calculations and 4.6×10^{-5} in the vorticity calculations.

These results indicate that a systematic error in the wind direction would have the greatest effect on the divergence calculations and a systematic error in the wind speed would have the greatest effect on the vorticity calculations. The magnitude of the difference resulting from these assumed systematic errors indicates,

however, that a systematic error of 10° and/or 20 cm sec^{-1} in the wind data could be tolerated without affecting the qualitative results of the vorticity and divergence calculations.

4.5 The Nature of the Experimental Errors

The crux of this study was the measurement of the wind characteristics at four tower locations near the edge of the city. The measurement of any parameter is subject to many sources of error. A few of the factors which limit the precision of the wind character measurements are the following:

(a) Instrument Calibration

The calibration techniques and operation precautions have been previously discussed in the chapter dealing with instruments. Certainly there were accuracy limitations in the vanes, anemometers, potentiometers, power supplies, counters, and recorders. Of paramount importance, however, was the net accumulation of these errors. To establish the confidence limits of the data and to test for the existence of major systematic errors, a set of experiments was conducted with all four towers in the same location.

A flat, open area was found to the west of Site #1. There were no major obstructions within .5 km of the test site and the upwind fetch was open to an even greater extent than that. These tests were conducted using the identical experimental procedure used during the experiments. The results of the four 15-minute tests are given in Table 3.

As can be seen from this table, there were no major systematic errors in the instruments. From these results the

TABLE 3. The 15-minute averages of wind speed and direction as read from the charts of the four towers in the same location.

TEST	TOWER #1		TOWER #2		TOWER #3		TOWER #4		MEAN		S.D.	
	DIR	SPD	DIR	SPD	DIR	SPD	DIR	SPD	DIR	SPD	DIR	SPD
1	93.8°	4.2	95.9°	4.1	94.9°	4.1	93.0°	4.2	94.4°	4.1	2.2°	0.02
2	90.2°	4.3	92.9°	4.2	91.9°	4.3	90.2°	4.3	91.3°	4.3	2.3°	0.03
3	83.1°	3.1	87.8°	3.1	85.6°	3.1	85.6°	3.0	85.5°	3.1	3.3°	0.03
4	70.1°	3.1	73.9°	3.0	71.2°	3.0	72.6°	3.0	72.0°	3.0	2.9°	0.01
MEAN	84.3°	3.7	87.6°	3.6	85.9°	3.6	85.4°	3.6	85.8°	3.6	2.7°	0.02

95% confidence limit of the wind direction was $\pm 5.3°$ and the wind speed ± 4.4 cm sec^{-1}.

During each experiment there was an attempt to instrument each of the sites in exactly the same manner so that some of the random errors involved in the operation of the tower would be minimized. Three examples of this type of error would be (1) the orientation of the boom, (2) the orientation of the vane on the potentiometer, and (3) the deviations of the tower from the vertical.

(b) Observer Skill

The sensitivity of the wind speed to observer error has been previously discussed in section 3.4. Observer error was also possible in the reading of the wind direction recording. To estimate the magnitude of this type of error the data from several of the experiments were redigitized several months after the initial analysis. The standard deviation between these two analysis was 0.8° (less than 1°).

(c) Chart Resolution

Limitations were placed on the determination of the wind direction and speed by the resolution of the scales on the Rustrak recorder and the wind speed calibration certificates.

(i) Wind direction

There were 50 scale lines (rectilinear) on the recording paper. With practise it was possible to read the trace to the nearest 1/4 of a space. This represented 1.8°

(ii) Wind speed

On the calibration certificate for 80 counts per minute and less there was a scale line for every 2 cm sec^{-1}. It was possible to read this graph to the nearest 1 cm sec^{-1}. On the certificate for 80 to 220 counts per minute there was a scale line every

5 cm sec^{-1}. With practise it was possible to read this graph to the nearest 2 cm sec^{-1}.

(d) Miscellaneous Errors

In any experiment involving more than one or two variables which influence the final measurement, there are many perturbations influencing the final reading. Many of these perturbations are random in nature and take such forms as line voltage fluctuations, potentiometer friction, and vibration of the tower in strong winds.

4.6 Drainage Effects

Anderson (1971) in a study of the winds at Toronto, Canada, assumed that the net wind field was given by the linear combination of

(i) the topographic wind
(ii) the heat island wind
(iii) the lake wind
and (iv) the mean wind.

In this study the mean wind was assumed to be the simple vector average of the wind measured at the four towers. When this mean wind was vectorially subtracted from the measured wind, the resulting perturbation would be a combination of the topographic wind and the heat island wind. Because there are no large lakes in the immediate Edmonton area, it was assumed that Anderson's lake wind would be zero.

It is difficult to determine the exact meso-scale topographic perturbation on the mean wind. Anderson (1971) has attempted to do this with a "smoothed" topography (i.e. the abrupt topographic perturbations were smoothed). The magnitude of the effect is a

function of both the speed and direction of the mean wind.

Although the magnitude of the topographic wind was not determined for the sites used in this study, some qualitative information was evaluated. Specifically the general slope of the terrain surrounding the sites were calculated. This was done using a topographic map[9]. The contour interval was 3.0 meters (10 ft.). The resulting slopes are given in Table 4. The directions given are the directions from the tower towards the highest land.

TABLE 4. The slopes of the four sites.

SITE	DIRECTION	SLOPE
1	270°	3.4 m/1 km
2	315°	5.5 m/1 km
3	260°	6.1 m/1 km
4	300°	2.3 m/1 km

The slopes given here are the general slopes of the surrounding area. Note that the slope at each site is out of the west or northwest, sloping towards the east or southeast. Although no magnitude of the topographic wind was determined it would have a similar effect at all of the towers.

4.7 Experiments #1 and #2

The first two experiments conducted on the nights of July 15, 1971 and July 19, 1971 respectively, are not presented in detail here. The synoptic situations in both of these experiments were similar to those experienced in experiments #3 and #4 respectively.

9. Edmonton Military Townplan (1963). Transverse Mercator Projection. Scale 1:25,000.

Thus it was decided that nothing new would be added in a presentation of these first two experiments.

4.8 Experiment #3 26 July 1971

During the daylight hours preceding experiment #3 there were only a few clouds over Edmonton. The winds were described as generally light. The mean temperature for the day was slightly below normal with a maximum temperature being recorded as 21.1°C, and the minimum 8.9°C. The most frequent wind direction observations were from the WSW and the WNW with the average speed for the day being 1.9 m sec^{-1}. There were 14.2 hours of bright sunshine.

The surface analysis for 06 GMT showed a large high pressure system, centred in northern Montana extending its influence over the Central Plains. A slowly moving Maritime warm front lingered about 200 km to the west of Edmonton. (See Figure 4).

The Stony Plain tephigram (Figure 5) showed near dry adiabatic lapse rates in the lower levels at 00 GMT (1700 MST) 26 July 1971. By 12 GMT (0500 MST) slight warming had taken place in the layer between 860 millibars (mb) and 680 mb. However, strong surface radiation during the night led to the formation of a sharp surface inversion over the rural areas. On the other hand the vertical temperature profile over the urban complex was quite different. Figure 6 shows that the temperature profile during the experiment was near dry adiabatic. The city vertical temperature profile remained near dry adiabatic throughout the night. (See Figure 7). A comparison of the urban and rural vertical temperature profiles shows that the lower layers of the atmosphere over the city were far less stable than the comparable layer over the rural site. In Figure 7 (as in all of the other figures of this type) the arrows indicate the times of sunset and sunrise.

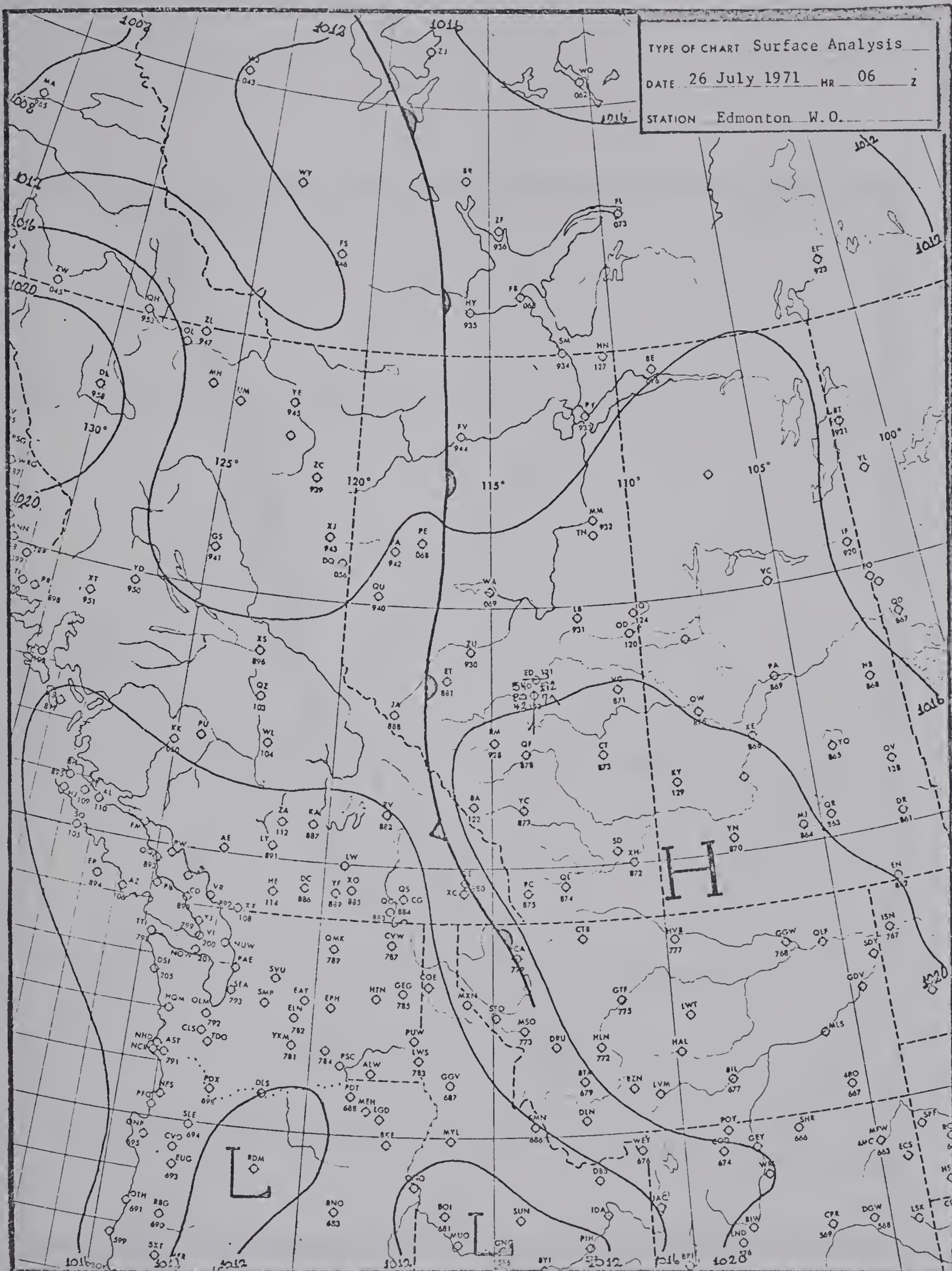

Figure 4. 26 July 1971, 0600 GMT Surface analysis.

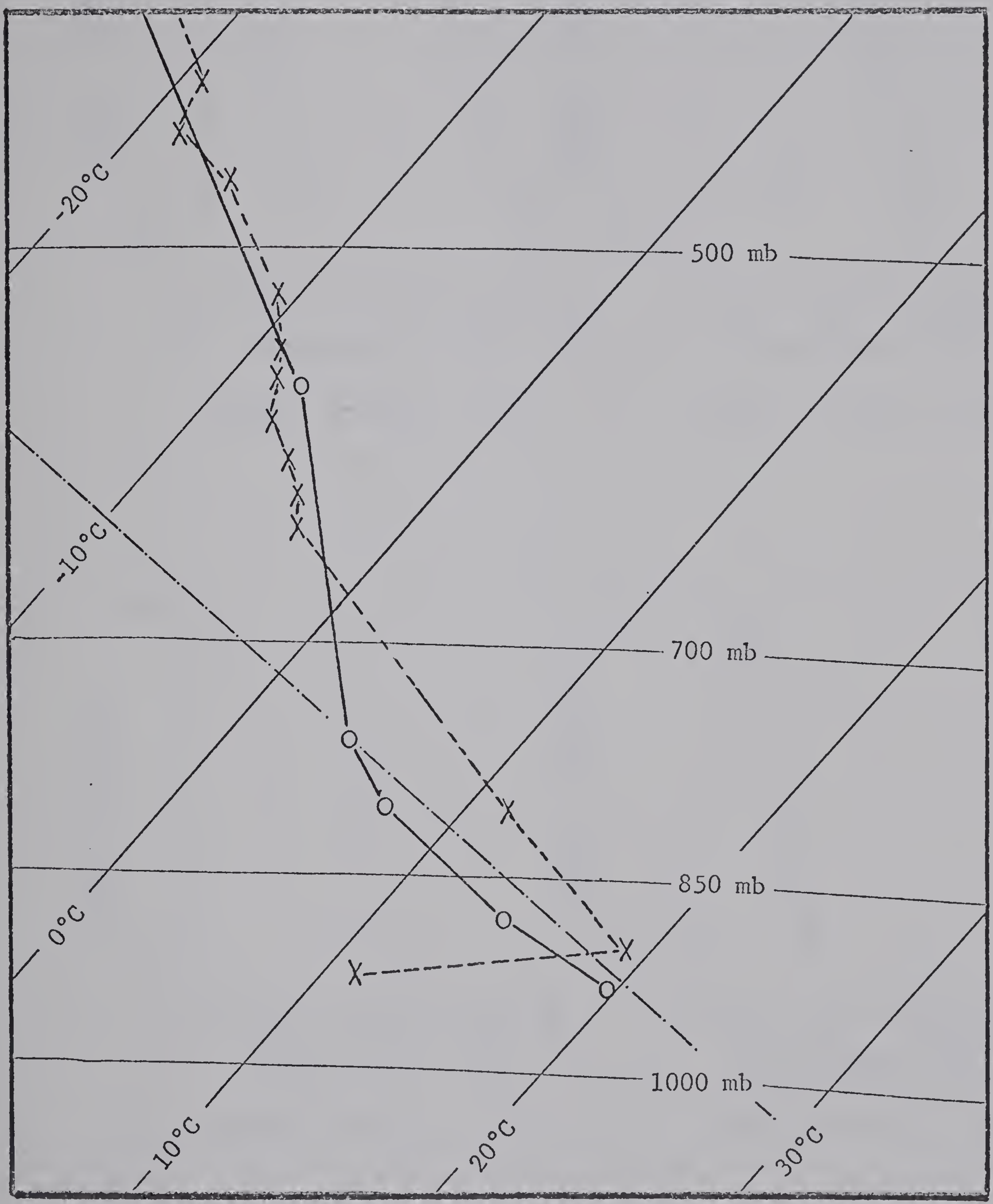

Figure 5. The Stony Plain tephigram for 26 July 1971.

———————— 0000 GMT
-------- 1200 GMT

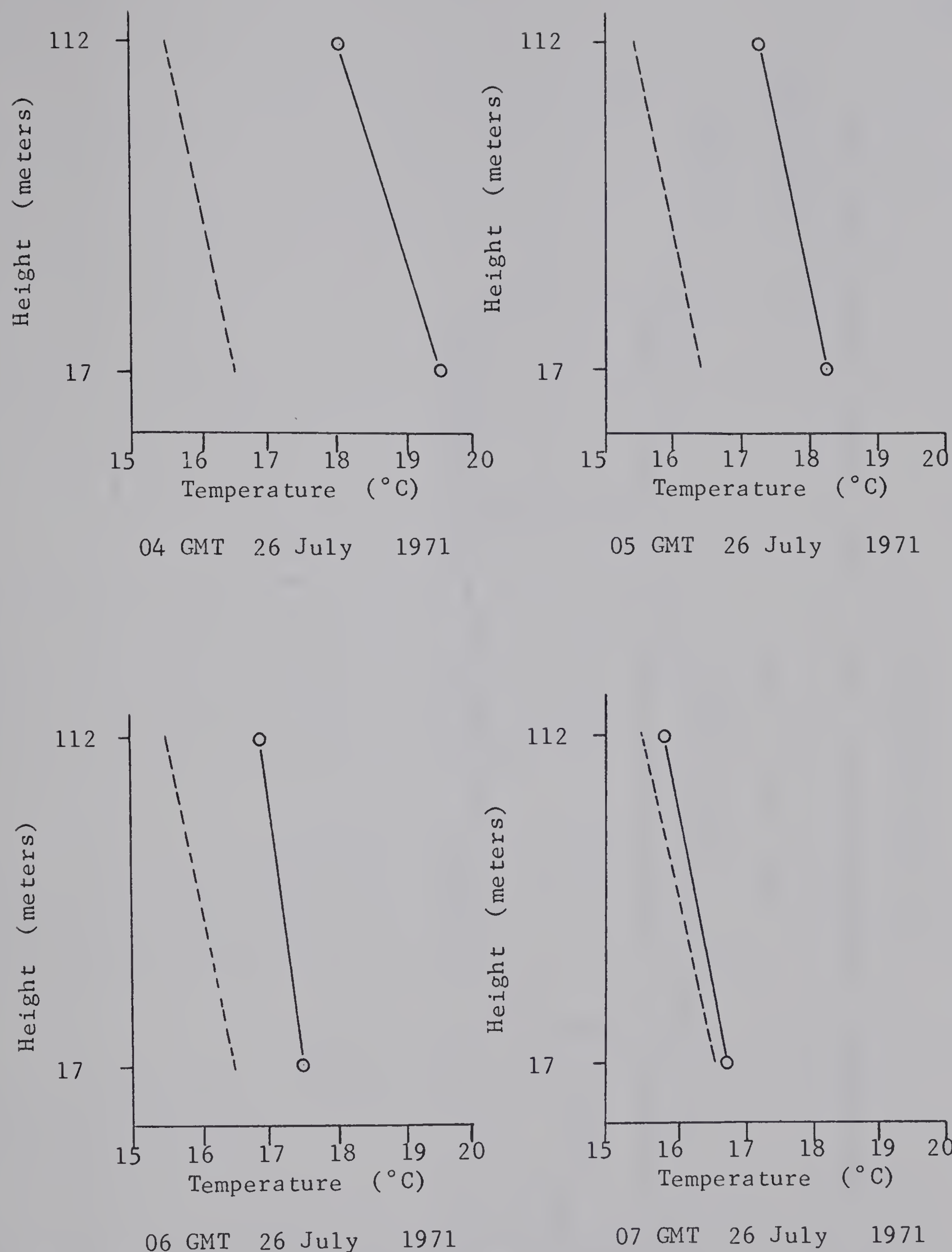

Figure 6. The CN Tower vertical temperature profiles.
----- dry adiabatic
_____ CN Tower

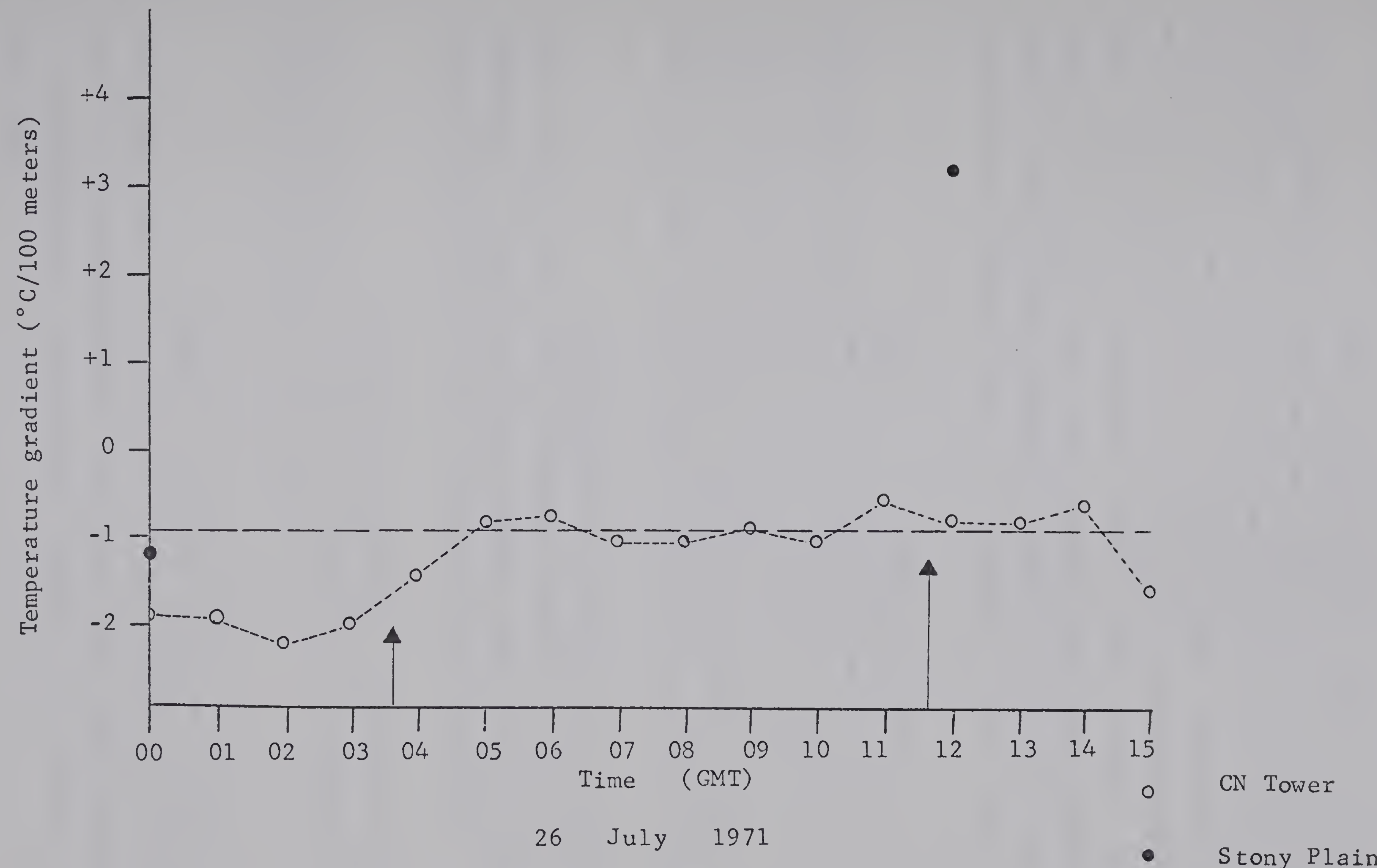

Figure 7. The vertical temperature gradient over the urban complex and the rural site.

(---- dry adiabatic)

Table 5 shows that the wind flow during the experiment was from the south-southeast. The speed of the mean flow was of the order of 1.7 m sec^{-1}. This same table also shows the perturbations from the mean flow at each of the four towers. These were obtained by vectorially subtracting the mean flow from the measured flow at each tower. Note that all speeds are m sec^{-1}. These results indicate that upwind of the city centre there was some perturbation added to the mean wind that was directed towards the centre of the city. Notice that the perturbation at Tower #1 had a very strong westerly component.

Tables 6 and 7 show the divergence and vorticity calculations respectively. In these tables (as is the case in all of the tables of this kind to follow) Triangle #1 refers to the calculations made using the data from Towers #2, #3, and #4 (i.e. the data from Tower #1 were excluded). Similarly Triangle #2 refers to the calculations made from the data excluding Tower #2 and so on.

From Triangle #4 in Table 6 it is quite evident that there was very strong convergence upwind of the city centre. The convergence is indicated by the negative sign. In all cases there was some weak oscillation of the intensity of the divergence.

Triangle #4 from Table 7 indicated that there was strong production of a counterclockwise vertical component of the vorticity upwind of the city centre.

Figures 8 through 10 show the isotherm and wind distribution over the city at 0400 GMT, 0500 GMT, and 0600 GMT, 26 July 1971. From these maps it can be seen that there was some evidence of a perturbation of the mean wind flow over the city due to the urban heat island.

TABLE 5. The half-hour average wind speed and direction, and the perturbation at each of the four towers. (Wind speeds m sec^{-1})

Time	Average	Perturbation Tower #1	Perturbation Tower #2	Perturbation Tower #3	Perturbation Tower #4
0400	166° 1.7	265° 0.5	114° 0.3	176° 0.4	155° 0.4
0430	154° 1.8	242° 0.5	160° 0.2	127° 0.4	178° 0.2
0500	163° 1.6	268° 0.8	137° 0.4	139° 0.6	140° 0.2
0530	179° 1.6	250° 0.4	212° 0.4	165° 0.5	121° 0.5
0600	174° 1.7	266° 0.5	165° 0.6	185° 0.6	93° 0.4
MEAN	167° 1.7	260° 0.5	160° 0.3	159° 0.5	131° 0.3

TABLE 6. Half-hour divergence ($x10^{-5}$ sec^{-1}) values for the four Bellamy triangles.

Time	Triangle #1	Triangle #2	Triangle #3	Triangle #4
0400	+ 7.1	+ 3.3	- 7.5	-38.9
0430	- 4.7	- 0.8	- 6.4	-45.6
0500	- 3.5	- 5.0	-14.7	-43.9
0530	- 1.3	+ 2.6	- 6.1	-38.0
0600	+ 3.5	+ 0.5	-14.4	-48.5
MEAN	+ 0.2	+ 0.1	- 9.8	-43.0

TABLE 7. Half-hour vorticity ($x10^{-5}$) values for the four Bellamy triangles. Positive values are counterclockwise.

Time	Triangle #1	Triangle #2	Triangle #3	Triangle #4
0400	-13.5	+ 0.4	+ 2.0	+13.0
0430	-11.0	- 0.7	+ 5.2	+12.8
0500	-16.4	- 2.7	+ 0.4	+17.5
0530	-11.3	+ 2.9	+10.1	+28.4
0600	-19.0	+ 1.1	+ 5.4	+18.6
MEAN	-14.2	+ 0.2	+ 4.6	+18.1

An interesting anomaly was discovered in the analysis of the wind data from the three Edmonton airports. This anomaly was present during all of the nights that experiments were conducted. If the wind data from the International Airport were used as the base value of the wind, the flow measured at the Industrial Airport had a greater westerly component than the International Airport, and the wind data from the Canadian Forces Base Namao had a greater westerly component than the International Airport but the magnitude of this component was less than that from the Industrial Airport. No analysis of the anomaly was attempted at times other than the nights of the experiments. However, this anomaly was present during every experiment. If it is assumed that the wind data from the three airports are correct (a very reasonable assumption) then this turning of the wind over the city aids in establishing the significance of the urban area in its effect upon the mean wind field.

The wind barbs on all of the maps of the temperature and wind distribution over the city are not the conventional wind barbs. Instead the full barb represents 1 m sec^{-1}, the half barb 0.5 m sec^{-1}, and the flag represents 5.0 m sec^{-1}. The isotherm spacing on all of these maps is 2C°.

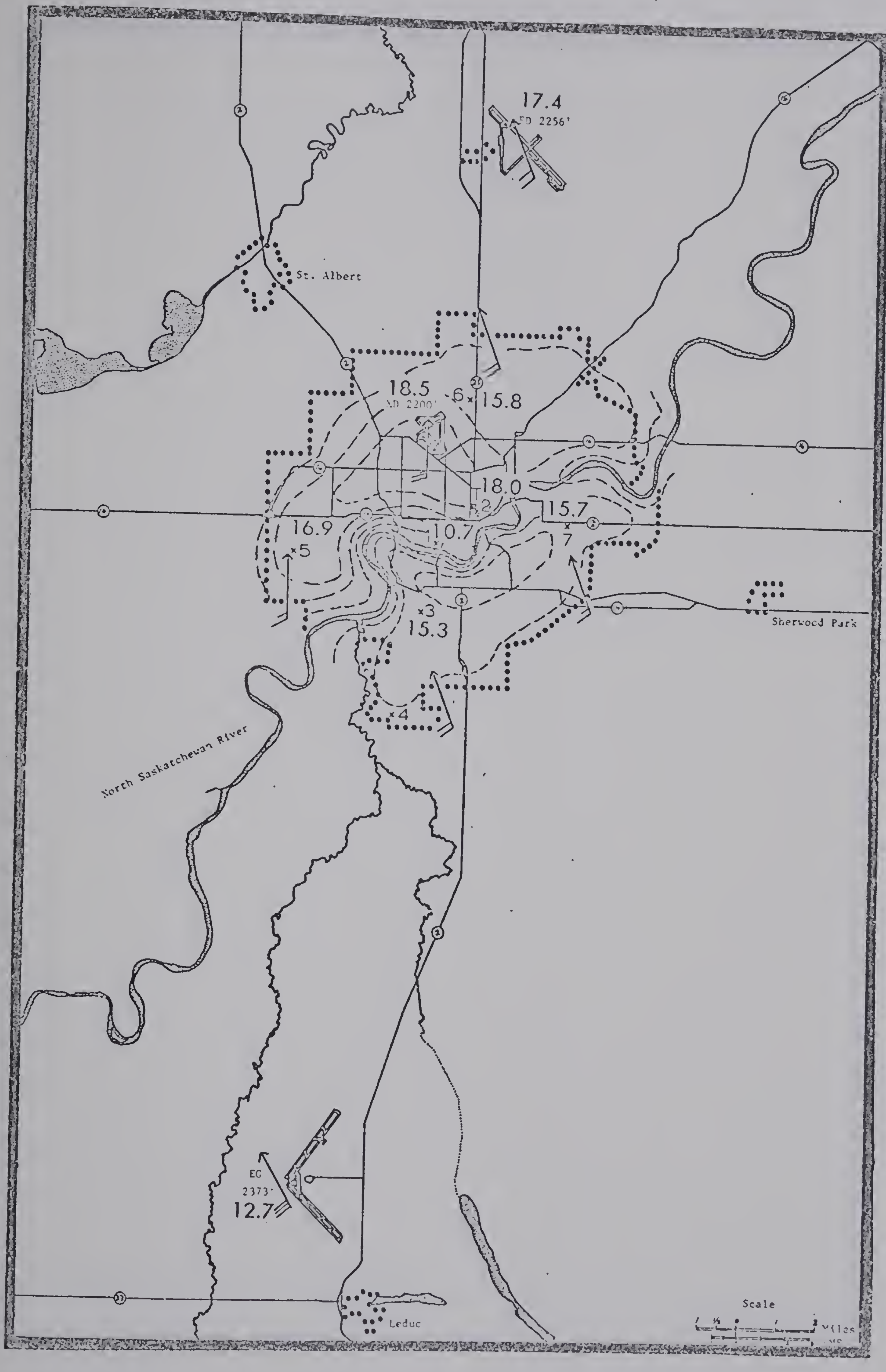

Figure 8 . Wind and temperature distribution 0400 GMT, July 26, 1971. Isotherm spacing 2C°.

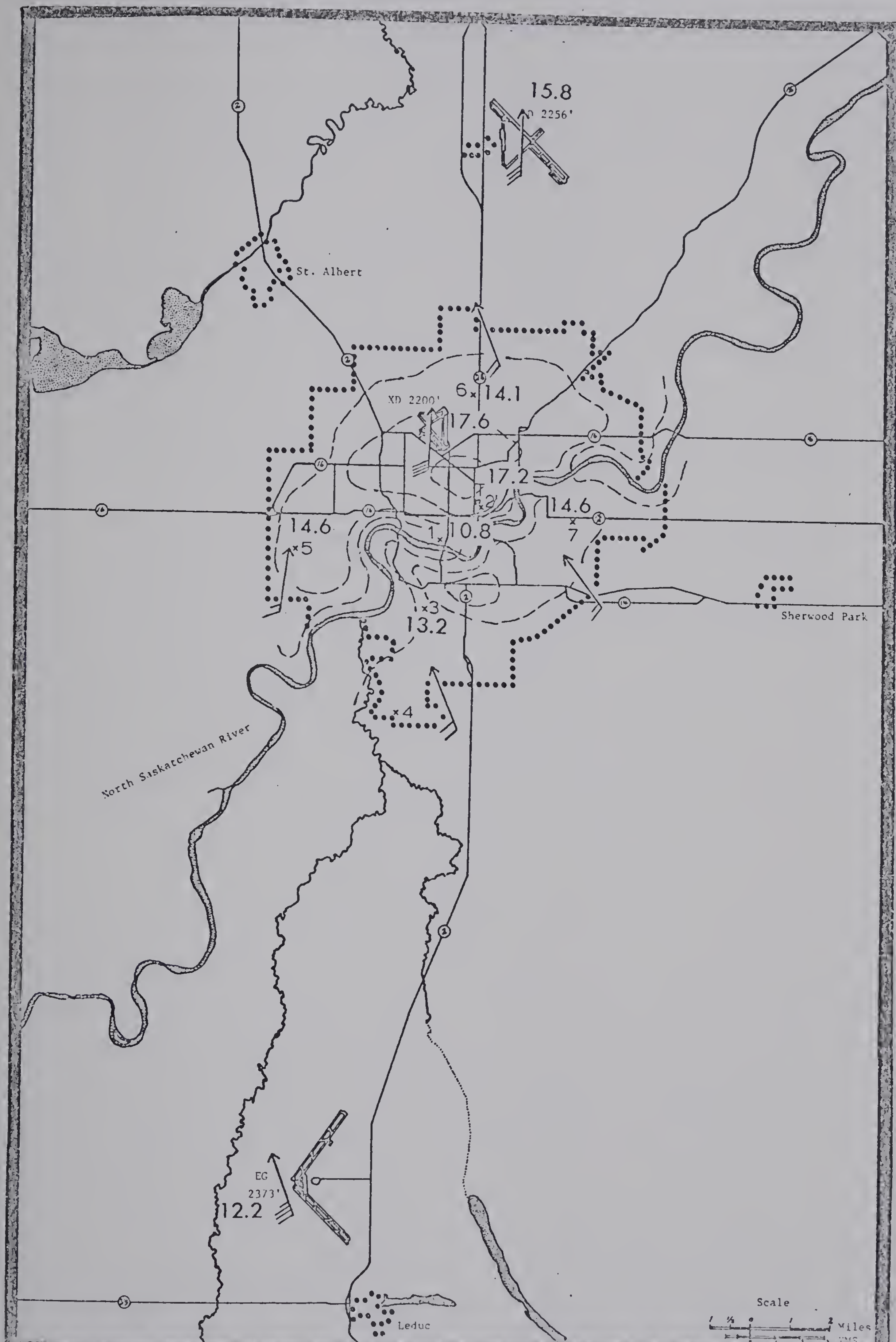

Figure 9. Wind and temperature distribution 0500 GMT, July 26, 1971. Isotherm spacing 2C°.

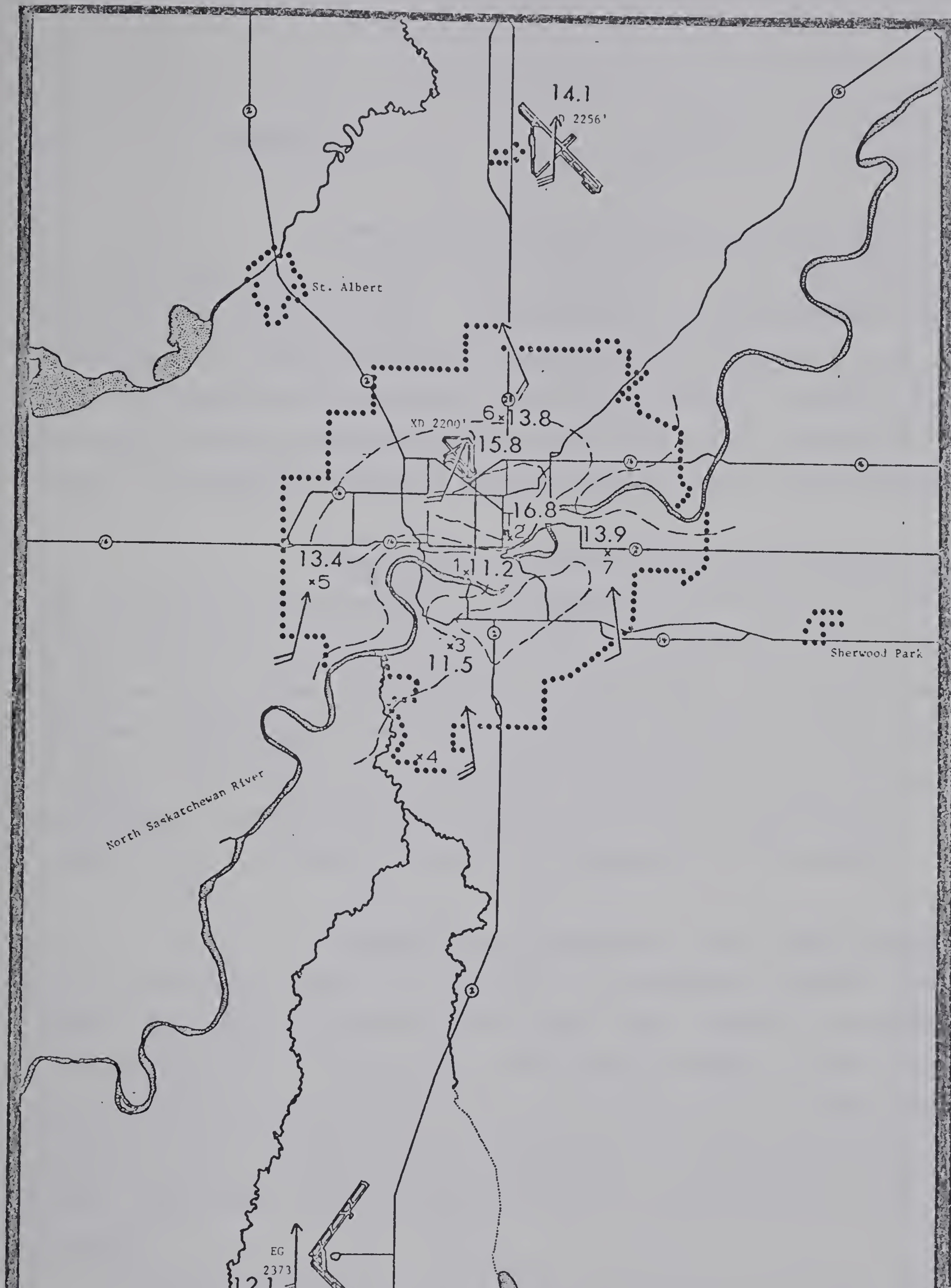

Figure 10. Wind and temperature distribution 0600 GMT, July 26, 1971. Isotherm spacing 2C°.

4.9 Experiment #4 01 August 1971

Some cloud was evident during the morning of July 31, 1971. However, it cleared early in the day so that 12.1 hours of bright sunshine was recorded. Temperatures were high with the maximum reaching 23.9°C and the minimum dropping only to 13.9°C. As was the case in Experiment #3 the winds were light. The most frequent observations of wind direction were SSE and S with a daily average of 3.5 m sec^{-1}. The maximum wind was from the NE at a speed of 5.5 m sec^{-1}.

Some patches of middle cloud were present during the running of the experiment. The reason for this can be seen from the 06 GMT surface analysis (Figure 11). A dominating high pressure cell centred northwest of Moose Jaw, Saskatchewan, with a weak pressure gradient extending over most of the Central Plains, set the general synoptic weather pattern. A weak warm front lying along the foothills northwest of Edmonton at that time was likely the source of the patchy middle cloud in evidence during the running of the experiment.

The Stony Plain radiosonde also showed evidence of this warm front (Figure 12). The layer from 880 mb to 500 mb also showed some warming between 00 GMT and 12 GMT. However, below 880 mb a strong surface inversion was established overnight. On the other hand, the urban temperature profile as shown by the CN Tower data in Figures 13 and 14 indicates the maintenence of lapse conditions overnight with only a slight tendency towards an isothermal profile after sunset.

The wind and temperature distributions over the city are shown in Figures 15, 16, and 17 for 0400 GMT, 0500 GMT, and 0600 GMT respectively. As was the case during Experiment #3 the predominant flow component was from the south-southeast (Table 8). There was less fluctuation from the mean as the experiment progressed than

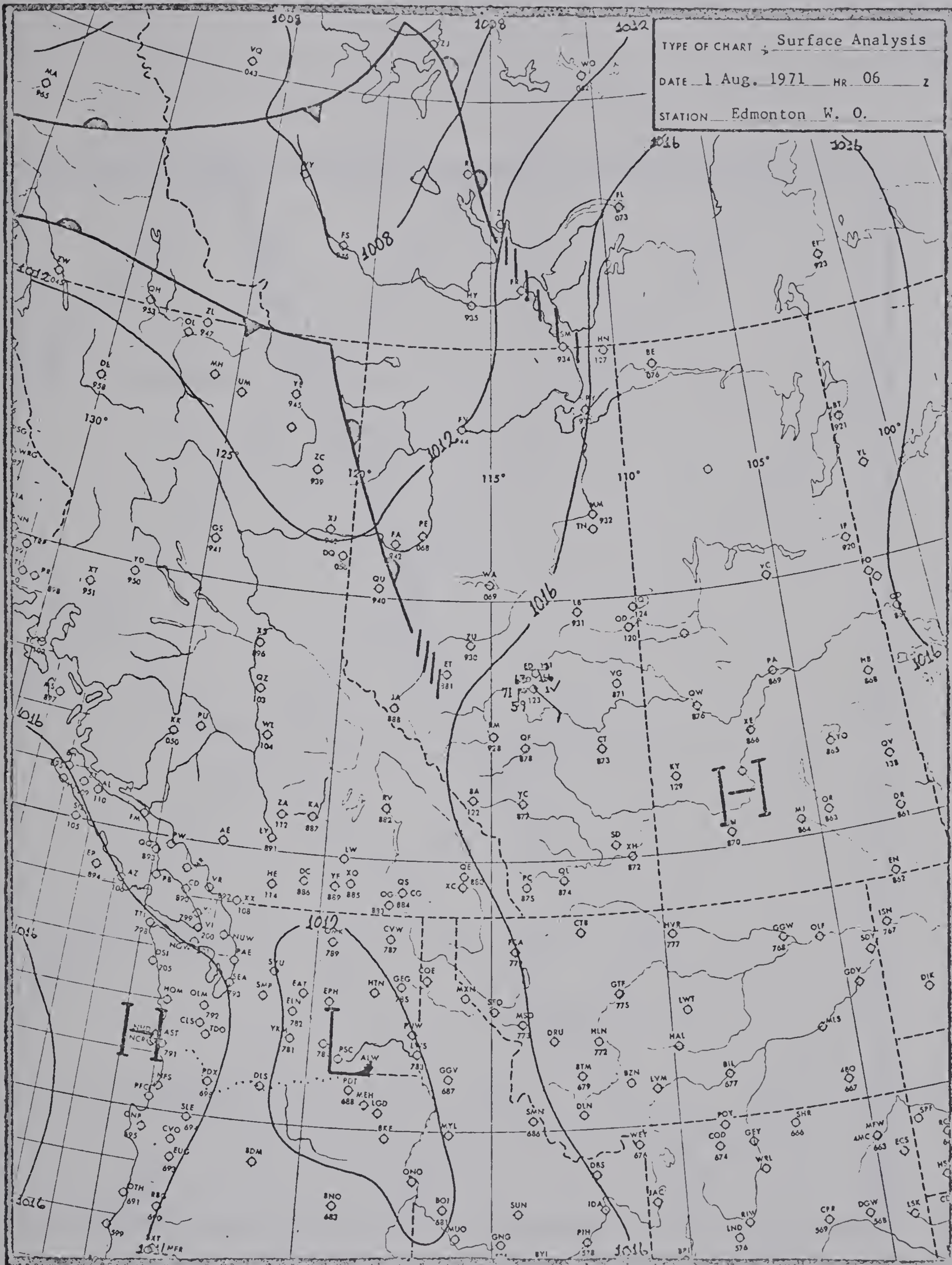

Figure 11. August 01, 1971, 0600 GMT Surface analysis.

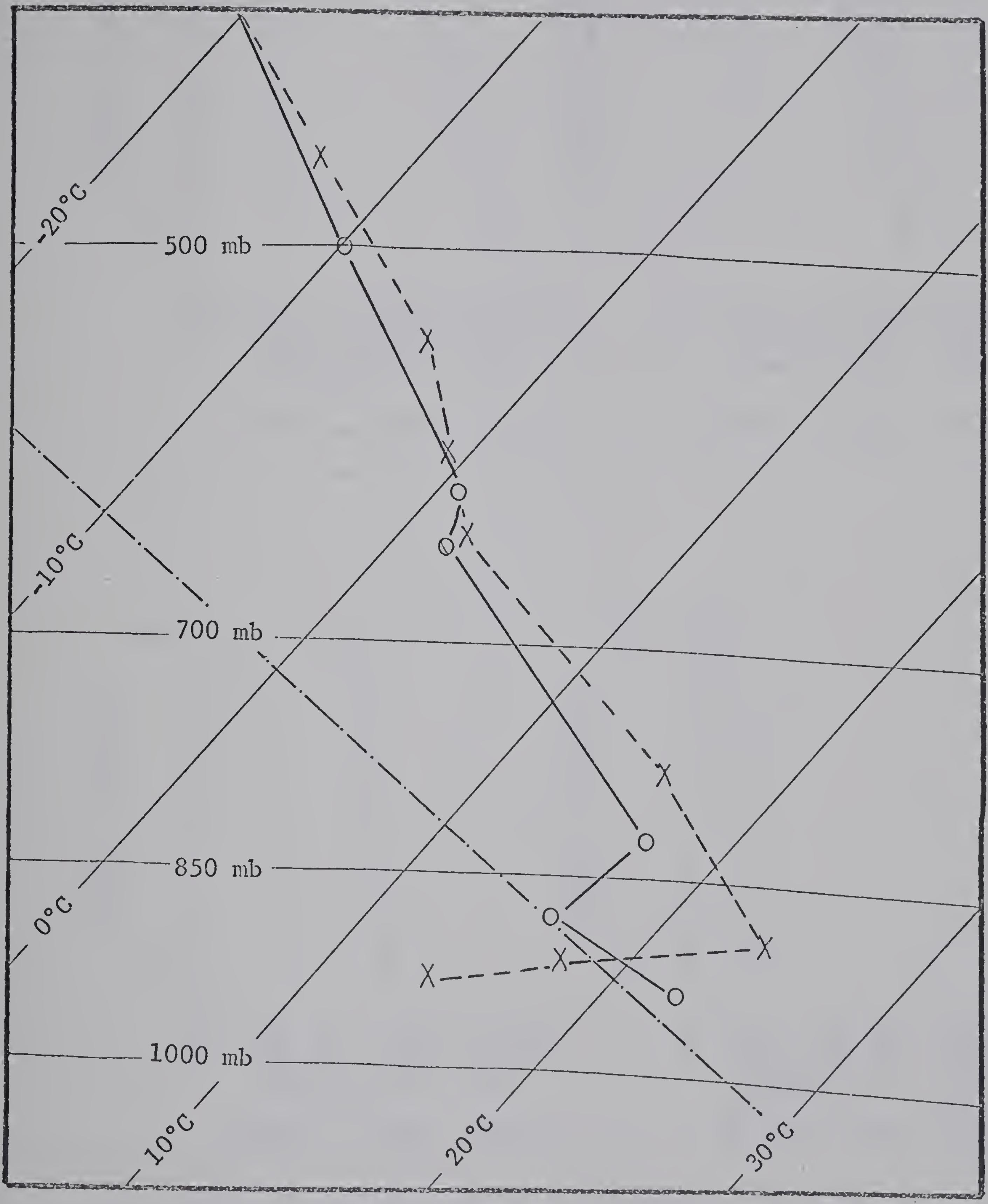

Figure 12. The Stony Plain tephigram for 01 August 1971.
——— 0000 GMT
- - - - - - 1200 GMT

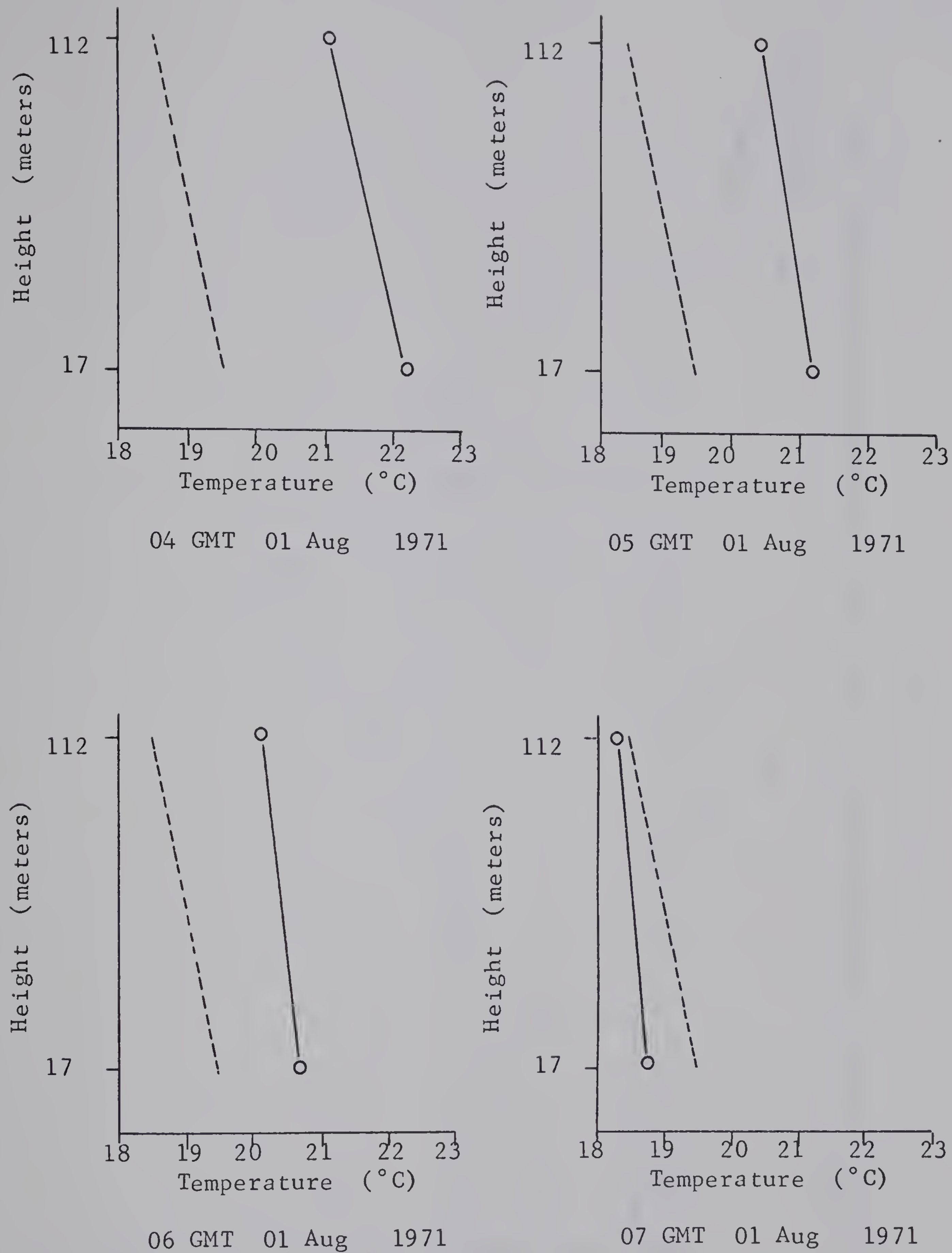

Figure 13. The CN Tower vertical temperature profile.
----- dry adiabatic
——— CN Tower

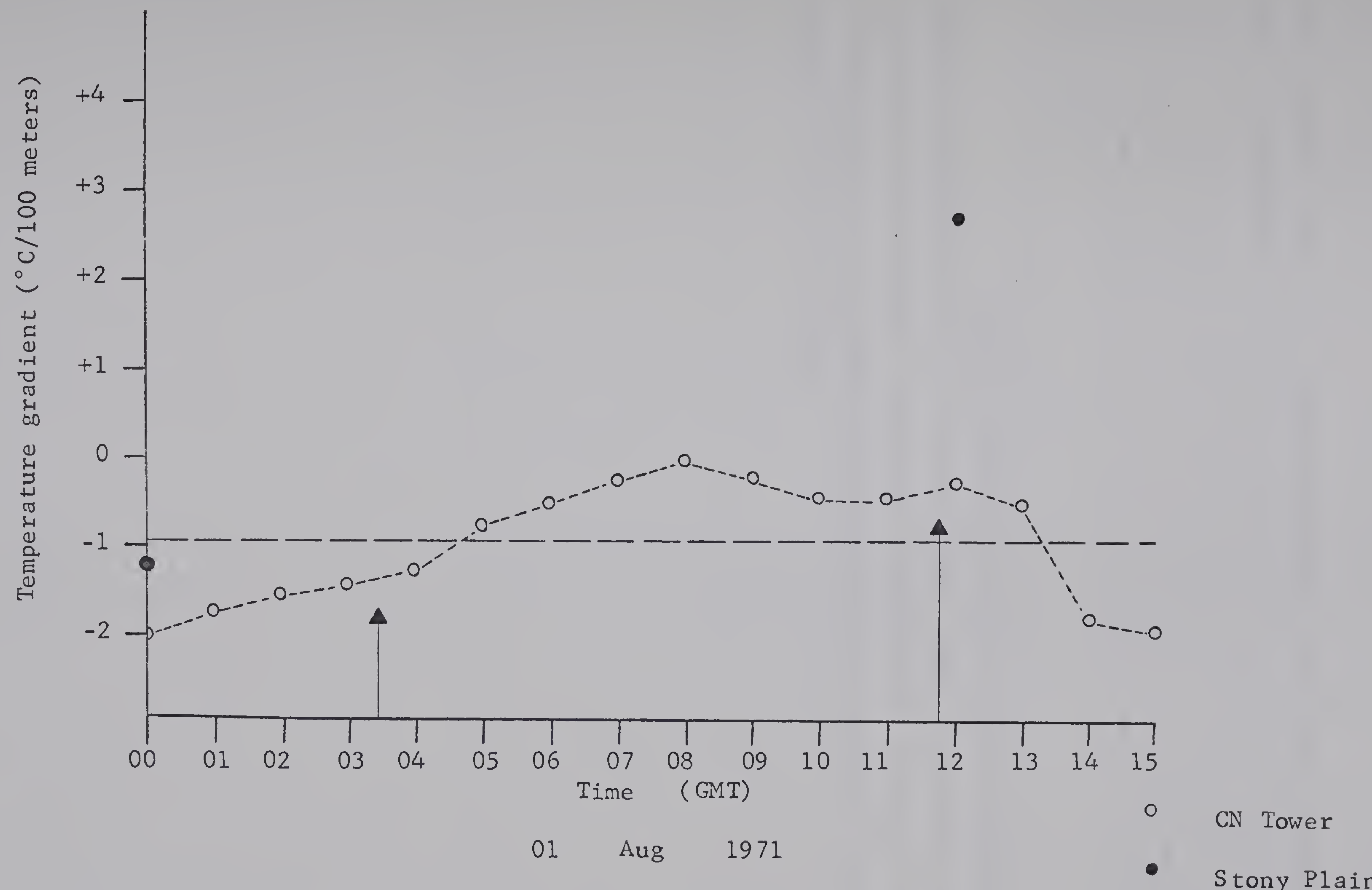

Figure 14. The vertical temperature gradient over the urban complex and the rural site.

(---- dry adiabatic)

had been the case in the other experiments. The perturbations from the mean at Towers #1, #2, and #3 were quite significant. Note that Tower #1 had a good west-southwest perturbation, Tower #2 showed a southerly perturbation and Tower #3 was east-southeasterly. These perturbations were almost exactly along the line joining the tower to the centre of the city.

Table 9 shows that there was net horizontal convergence calculated at all of the triangles. Again the upwind Triangle #4 indicated the strongest convergence. Triangle #4 in Table 10 also re-established the net counterclockwise vertical component of the vorticity upwind of the city centre.

TABLE 8. The half-hour average wind speed and direction, and the perturbation at each of the four towers. (Wind speeds m sec^{-1})

		Perturbation			
Time	Average	Tower #1	Tower #2	Tower #3	Tower #4
0400	153° 1.8	247° 0.5	161° 0.4	103° 0.6	265° 0.3
0430	161° 1.6	261° 0.4	239° 0.5	110° 0.5	92° 0.3
0500	150° 1.8	248° 0.7	145° 0.3	92° 0.5	158° 0.1
0530	156° 1.8	254° 0.5	197° 0.4	118° 0.6	91° 0.2
0600	156° 1.7	255° 1.0	196° 1.0	114° 0.9	125° 0.6
MEAN	155° 1.7	253° 0.6	193° 0.5	108° 0.6	123° 0.2

TABLE 9. Half-hour divergence ($\times 10^{-5}$ sec^{-1}) values for the four Bellamy triangles.

Time	Triangle #1	Triangle #2	Triangle #3	Triangle #4
0400	-14.2	- 6.6	- 8.2	-49.6
0430	-15.4	- 6.0	- 5.3	-44.5
0500	- 9.3	- 7.9	-12.3	-42.9
0530	-13.3	- 5.9	- 9.9	-51.6
0600	-24.9	-15.0	-23.3	-58.6
MEAN	-15.4	- 8.3	-11.8	-49.4

TABLE 10. Half-hour vorticity ($\times 10^{-5}$) values for the four Bellamy triangles. Positive values are counterclockwise.

Time	Triangle #1	Triangle #2	Triangle #3	Triangle #4
0400	-11.7	- 5.0	+ 2.4	+15.5
0430	- 3.4	+ 0.7	+ 8.4	+30.6
0500	- 6.0	+ 1.6	+ 4.6	+14.7
0530	-10.9	- 1.0	+ 7.3	+21.8
0600	-15.4	+ 1.9	+14.1	+29.2
MEAN	- 9.5	- 0.3	+ 7.3	+22.4

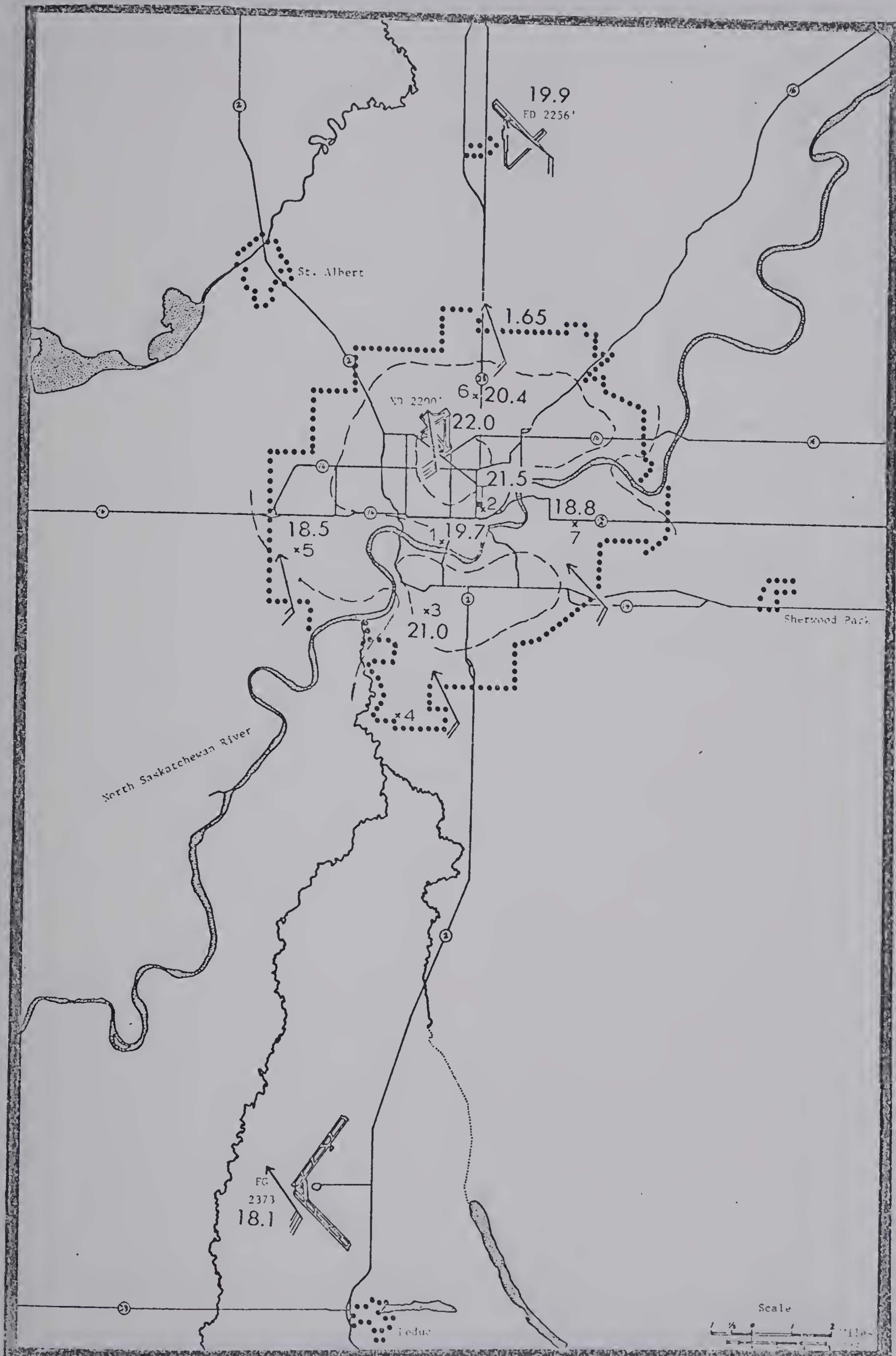

Figure 15. Wind and temperature distribution 0400 GMT 01 August 1971. Isotherm spacing 2C°.

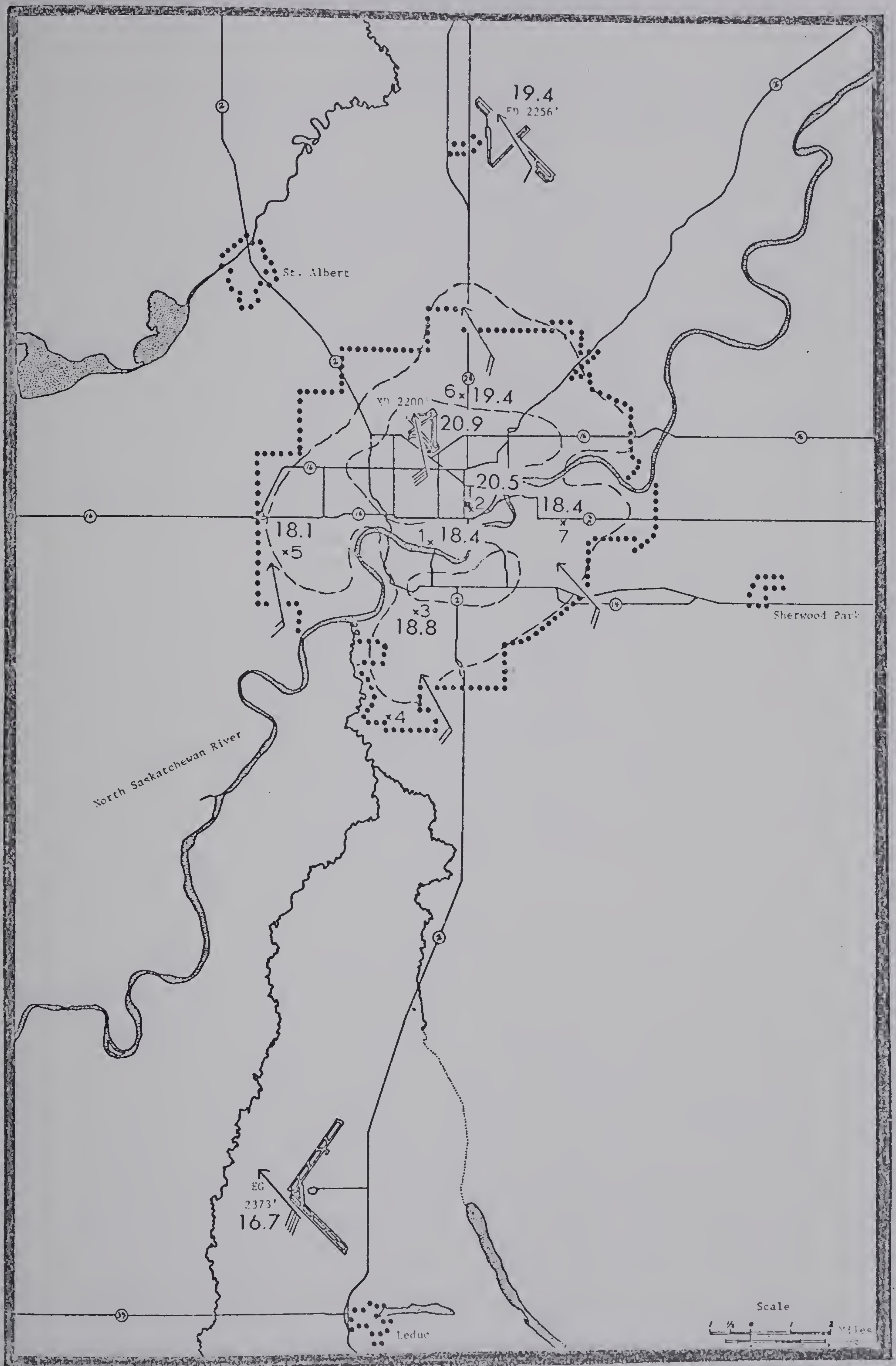

Figure 16. Wind and temperature distribution 0500 GMT 01 August 1971. Isotherm spacing 2C°.

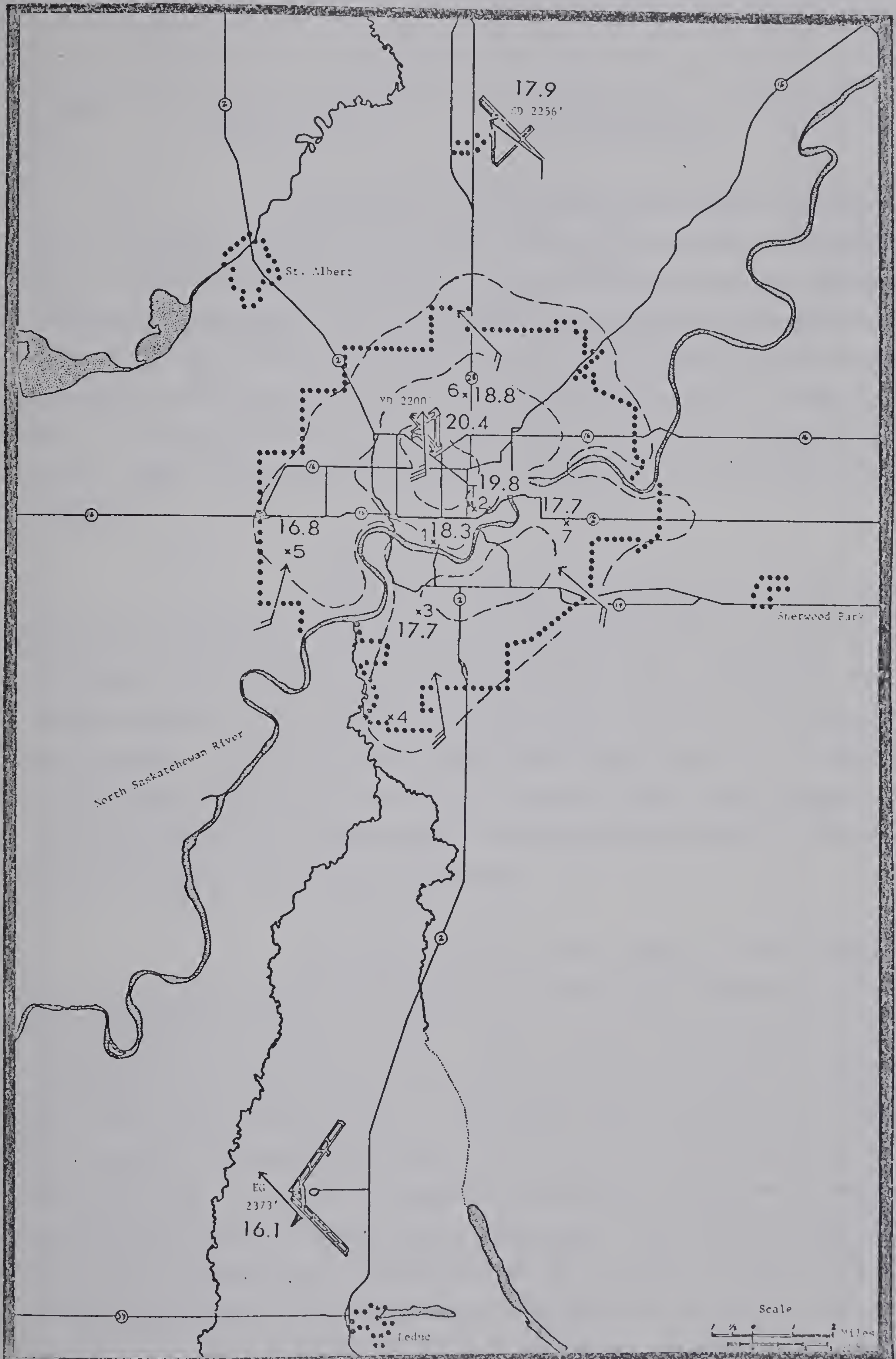

Figure 17. Wind and temperature distribution 0600 GMT 01 August 1971. Isotherm spacing 2C°.

4.10 Experiment #5 11 August 1971

Experiment #5 conducted on the night of August 10, 1971, included stronger geostrophic winds than had been encountered on any of the previous experiments. The day was warm with the maximum temperature reaching 27.2°C. Overnight the temperature dropped to a minimum of 15.0°C. The average wind was 2.5 m sec^{-1} with the most frequent direction being recorded as W. The maximum wind was also from the west but at a speed of 5.0 m sec^{-1}. There were 14.4 hours of bright sunshine. Only a few cirrus clouds were present during the run of the experiment.

A large low pressure area centred near Hay River, Northwest Territories (NWT) was the dominating feature of the 06 GMT 11 August 1971 surface analysis (Figure 18). This system gave cool, rainy weather to the northern portions of the province. The central and southern regions, however, experienced sunny skies as a series of small high pressure cells drifted eastward through these regions. The resulting pressure gradient gave the moderate geostrophic flow over the Edmonton region during the experiment.

The air over the central region of the province was also fairly dry as was indicated in the 00 GMT radiosonde ascent from Stony Plain (Figure 19). At least in the lowest levels of the atmosphere the sounding showed nearly dry adiabatic lapse conditions. The clear skies overnight led to strong surface radiation resulting in the surface inversion which was evident on the 12 GMT sounding. As had been the case in all of the previous experiments there was some warming of the 700 mb to 850 mb layer overnight. The temperature profile over the city was quite different from the profile on any of the previous experiments. The temperature data from the CN Tower (Figures 20 and 21) showed that lapse conditions prevailed throughout the daylight hours. After sunset a near isothermal profile was established. Further

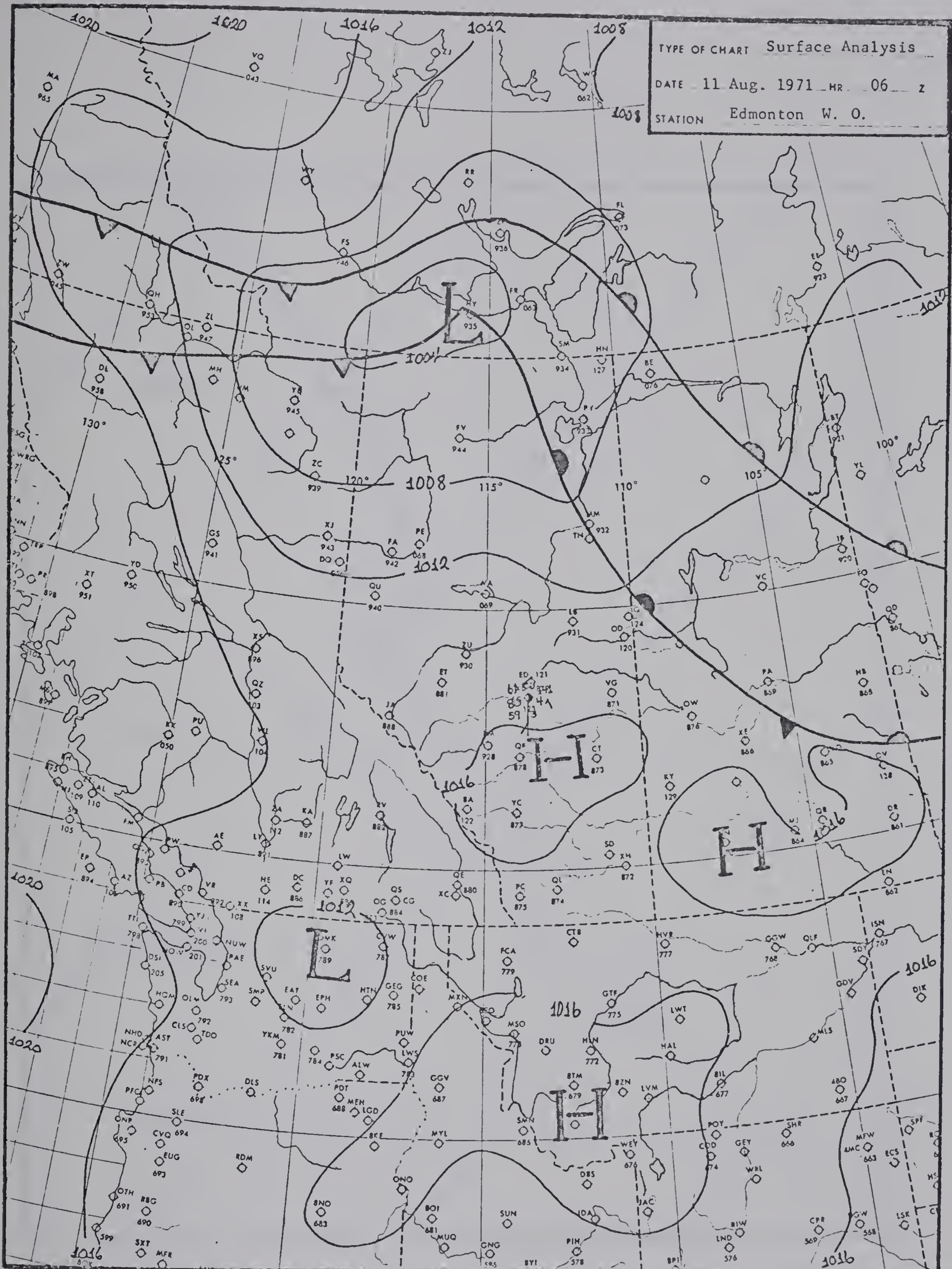

Figure 18. August 11, 1971, 0600 GMT Surface analysis.

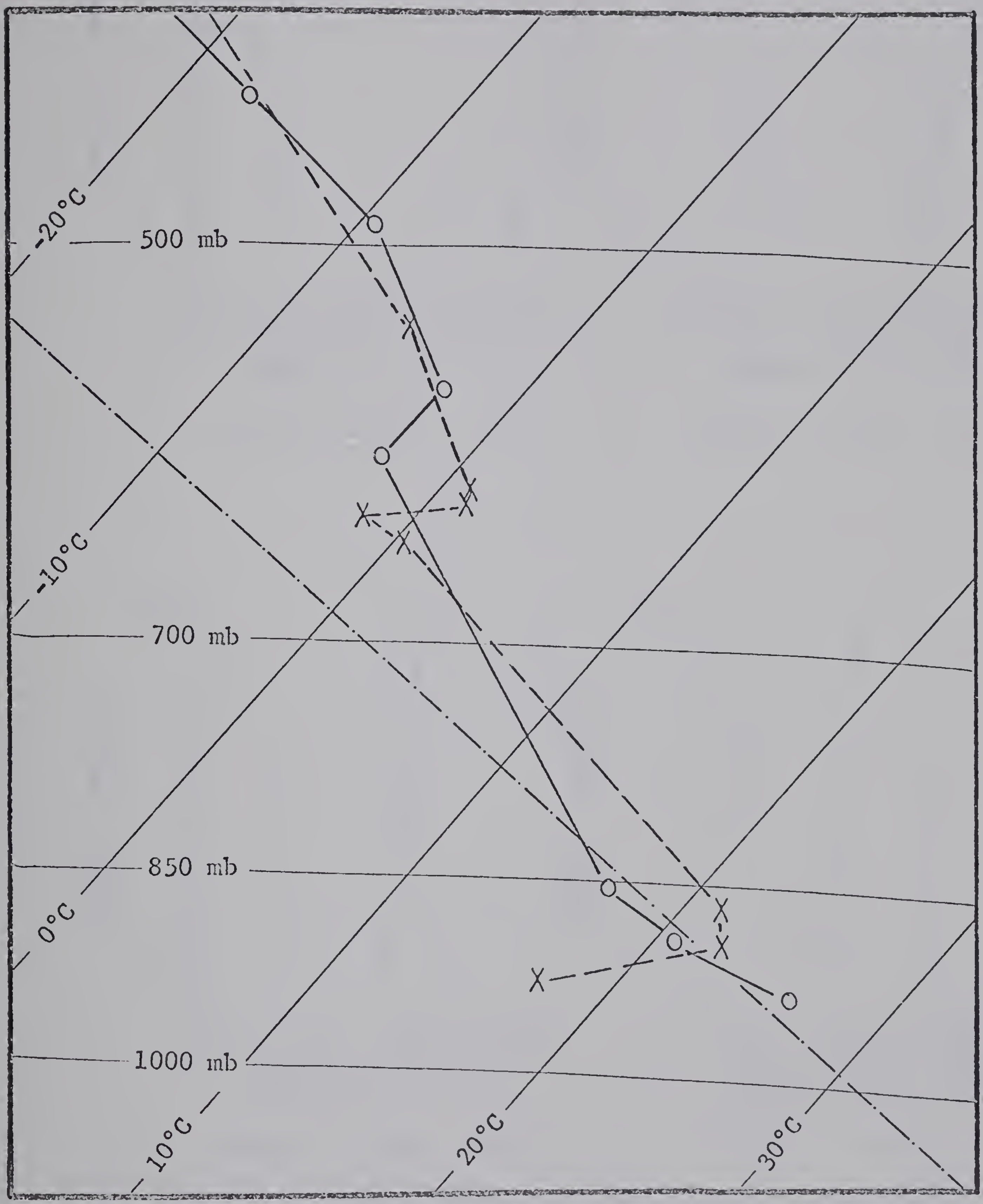

Figure 19. The Stony Plain tephigram for 11 August 1971.

——— 0000 GMT

------ 1200 GMT

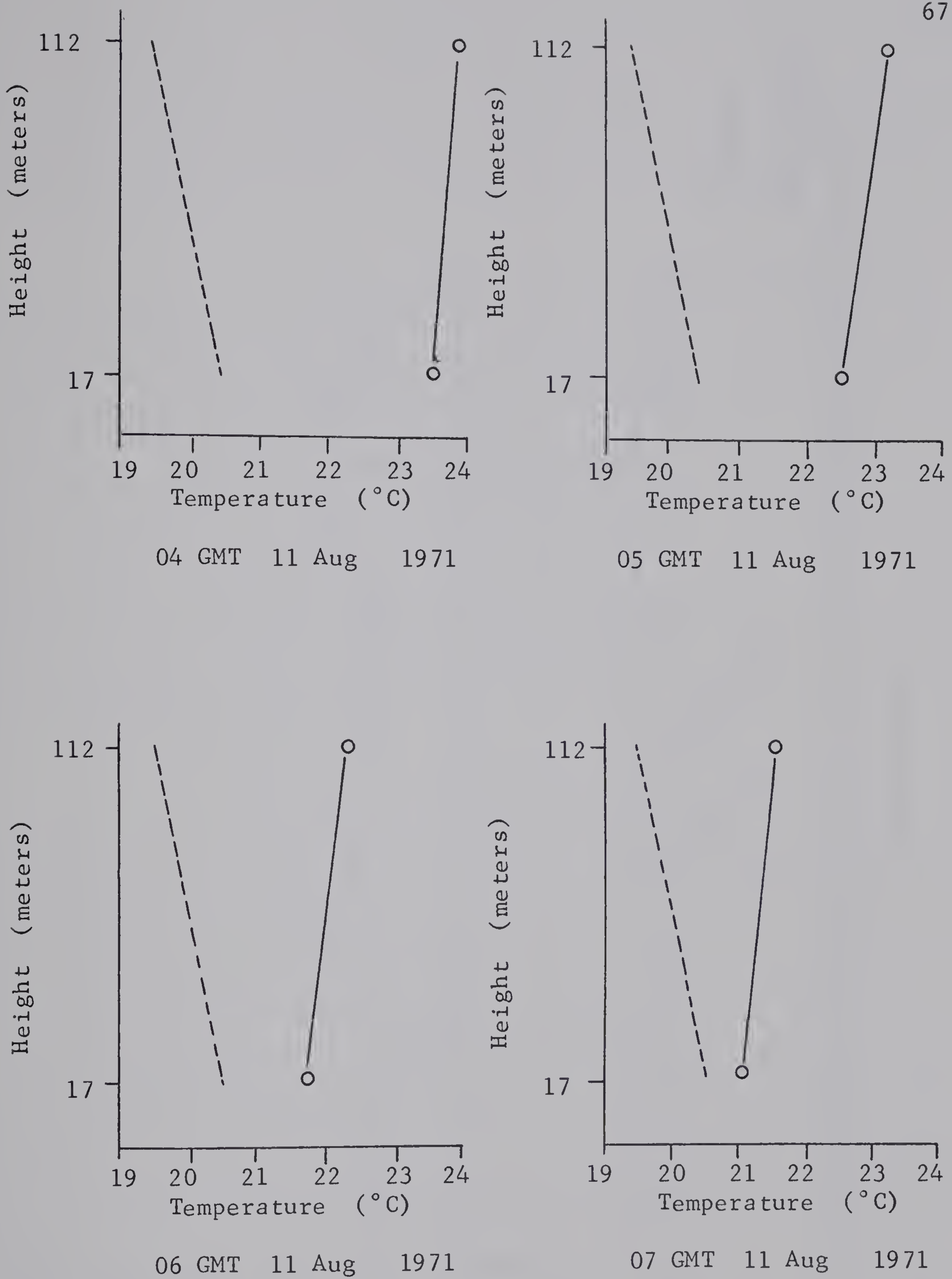

Figure 20. The CN Tower vertical temperature profiles.
----- dry adiabatic
——— CN Tower

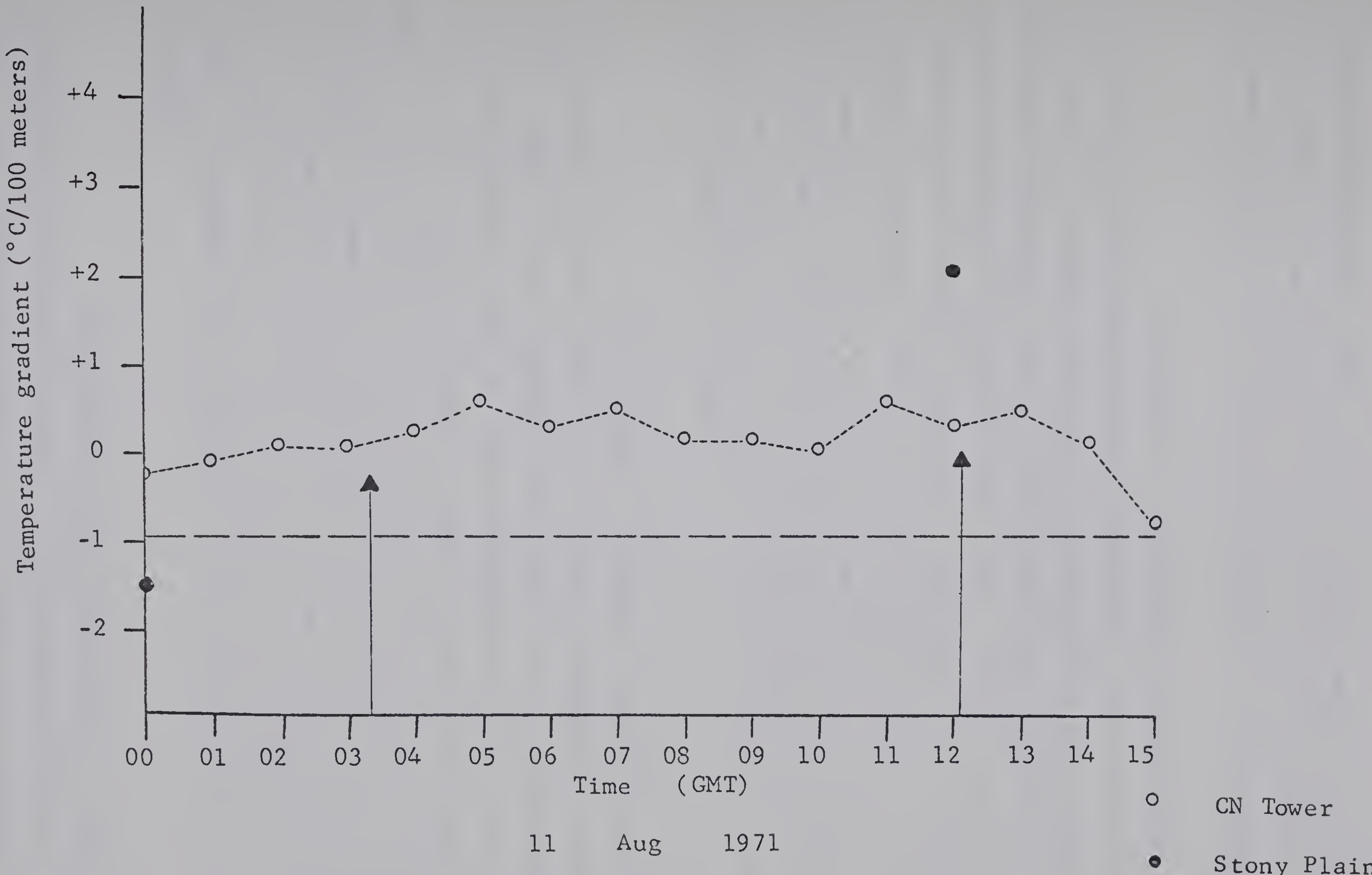

Figure 21. The vertical temperature gradient over the urban complex and the rural site.

(---- dry adiabatic)

surface cooling then gave rise to a slight temperature inversion. Some oscillation of the intensity of this inversion was noticed with the maximum strength of the inversion being near 1C°/100 meters.

The wind and temperature distributions over the city during this experiment are summarized in the maps in Figures 22, 23, and 24. The mean flow during the experiment was stronger than it had been during any of the previous experiments (Table 11). It was also interesting to note from this table that the strength of the perturbations was stronger during this experiment than it had been in the previous experiments. Vukovich (1971) suggested that the perturbation flow would be stronger in the case when there was a stable layer over the city than in the case when there was a layer of unstable air over the urban complex. The observations obtained here would tend to reinforce the analysis by Vukovich.

The analysis of the wind speeds at each of the four towers for this experiment was quite interesting. During the initial stages of the experiment the upwind Tower #2 had greater speeds than the downwind Tower #4. The 0500 GMT wind speed at Tower #2 was 2.6 m sec^{-1} compared to the 2.5 m sec^{-1} at Tower #4. However, by 0600 GMT the wind at Tower #4 had increased in speed to 3.1 m sec^{-1} whereas the speed at Tower #2 had decreased to 2.2 m sec^{-1}. For the remainder of the experiment the speed at Tower #4 was consistently higher than the speed at Tower #2. Even an analysis of the components of the flow showed a stronger south component at the downwind site than upwind of the city.

This type of wind flow manifests itself in the divergence calculations in Table 12. The upwind Triangle #4 again showed very strong convergence. On the other hand downwind of the city the Triangles #2 and #3 both showed some divergence. Triangle #4 in Table 13 showed a counterclockwise vertical component of the vorticity.

TABLE 11. The half-hour average wind speed and direction, and the perturbation at each of the four towers. (Wind speeds m sec^{-1})

Time	Average	Perturbation Tower #1	Tower #2	Tower #3	Tower #4
0430	169° 2.0	228° 1.2	123° 0.6	102° 0.8	208° 0.7
0500	172° 2.2	221° 0.9	148° 0.5	91° 0.8	237° 0.6
0530	175° 1.7	240° 0.8	184° 0.4	95° 0.6	133° 0.1
0600	187° 2.1	210° 0.9	112° 0.3	122° 0.6	203° 1.1
0630	189° 2.1	202° 0.8	116° 0.4	106° 0.6	224° 1.1
0700	195° 1.6	237° 0.4	116° 0.4	96° 0.8	248° 0.9
0730	200° 2.1	204° 0.7	139° 0.7	128° 0.8	230° 1.1
MEAN	184° 1.9	220° 0.8	134° 0.4	105° 0.7	223° 0.8

TABLE 12. Half-hour divergence (x10^{-5} sec^{-1}) values for the four Bellamy triangles.

Time	Triangle #1	Triangle #2	Triangle #3	Triangle #4
0430	- 9.0	- 2.4	-13.6	-41.5
0500	-18.2	- 5.8	- 9.8	-47.7
0530	-16.5	-10.9	-14.1	-36.8
0600	- 2.8	- 8.5	- 1.2	-33.8
0630	- 6.4	+ 2.7	+ 2.5	-21.8
0700	-14.5	- 5.1	+ 0.3	-19.0
0730	- 5.4	- 0.6	+ 5.2	- 4.9
MEAN	-10.4	- 1.9	- 4.4	-29.4

TABLE 13. Half-hour vorticity (x10^{-5}) values for the four Bellamy triangles. Positive values are counterclockwise.

Time	Triangle #1	Triangle #2	Triangle #3	Triangle #4
0430	-20.0	- 0.5	+10.0	+23.8
0500	-15.3	- 5.8	+ 9.2	+33.4
0530	- 4.8	+ 2.9	+ 8.7	+34.8
0600	-22.2	- 3.2	+10.7	+32.4
0630	- 8.6	- 3.8	+ 3.8	+36.3
0700	- 8.9	-11.5	- 6.0	+36.3
0730	+ 2.4	- 3.2	- 2.3	+44.8
MEAN	-11.1	- 3.6	+ 4.9	+34.5

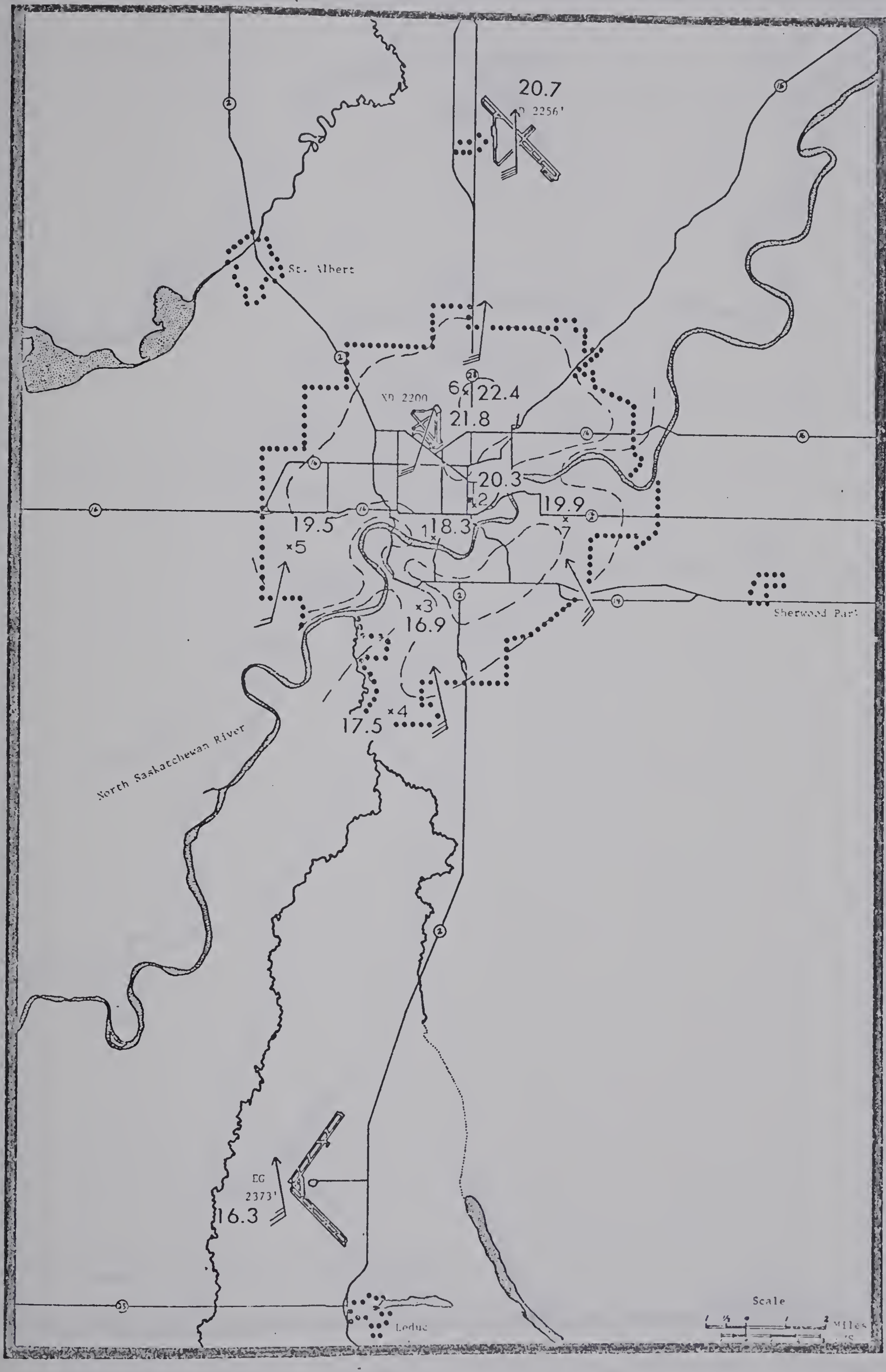

Figure 22. Wind and temperature distribution 0500 GMT, 11 August 1971. Isotherm spacing 2C°

Figure 23. Wind and temperature distribution 0600 GMT, 11 August 1971. Isotherm spacing 2C°.

Figure 24. Wind and temperature distribution 0700 GMT 11 August 1971. Isotherm spacing 2C°.

4.11 Experiment #6 20 August 1971

Experiment #6 conducted on the night of the 19th of August 1971, contained some of the most interesting results of the set of experiments. It was during this experiment that the geostrophic winds diminished to near 1 m sec^{-1}.

The day had been quite warm with the maximum temperature reaching a high of 27.2°C. The overnight temperature dropped 16.6C° to a minimum temperature of 10.6°C. At no time during the day had any great amount of cloud been present. There were 13.5 hours of bright sunshine. The average wind speed for the day was 3.3 m sec^{-1}. The most frequent direction for the day was SSW. However, by evening the winds had backed to a more east to southeast direction. During the experiment the winds veered slightly. The maximum wind for the day had been S at 5.0 m sec^{-1}. The average of the hourly observations of the wind speed for the three Edmonton airports for the duration of the experiment was 2.8 m sec^{-1}. The winds at Canadian Forces Base Namao were reported as calm during the last two hours of the experiment.

The surface analysis for 06 GMT 20 August 1971 (Figure 25) indicated a weak to moderate pressure gradient across the province. The highest pressures were in the southeast and decreased towards a low pressure area centred northwest of the region. A tongue of very warm air covered the Rocky Mountains south and west of Edmonton.

The 00 GMT and 12 GMT 20 August 1971 tephigrams from Stony Plain (Figure 26) were again very similar to those from the other nights of the experiments. There was a near dry adiabatic lapse profile in the lowest levels of the atmosphere during the late afternoon. Some warming took place in the levels above 880 mb overnight as would be expected with the approaching tongue of warm air. The nearly clear skies overnight resulted in the formation of a very strong

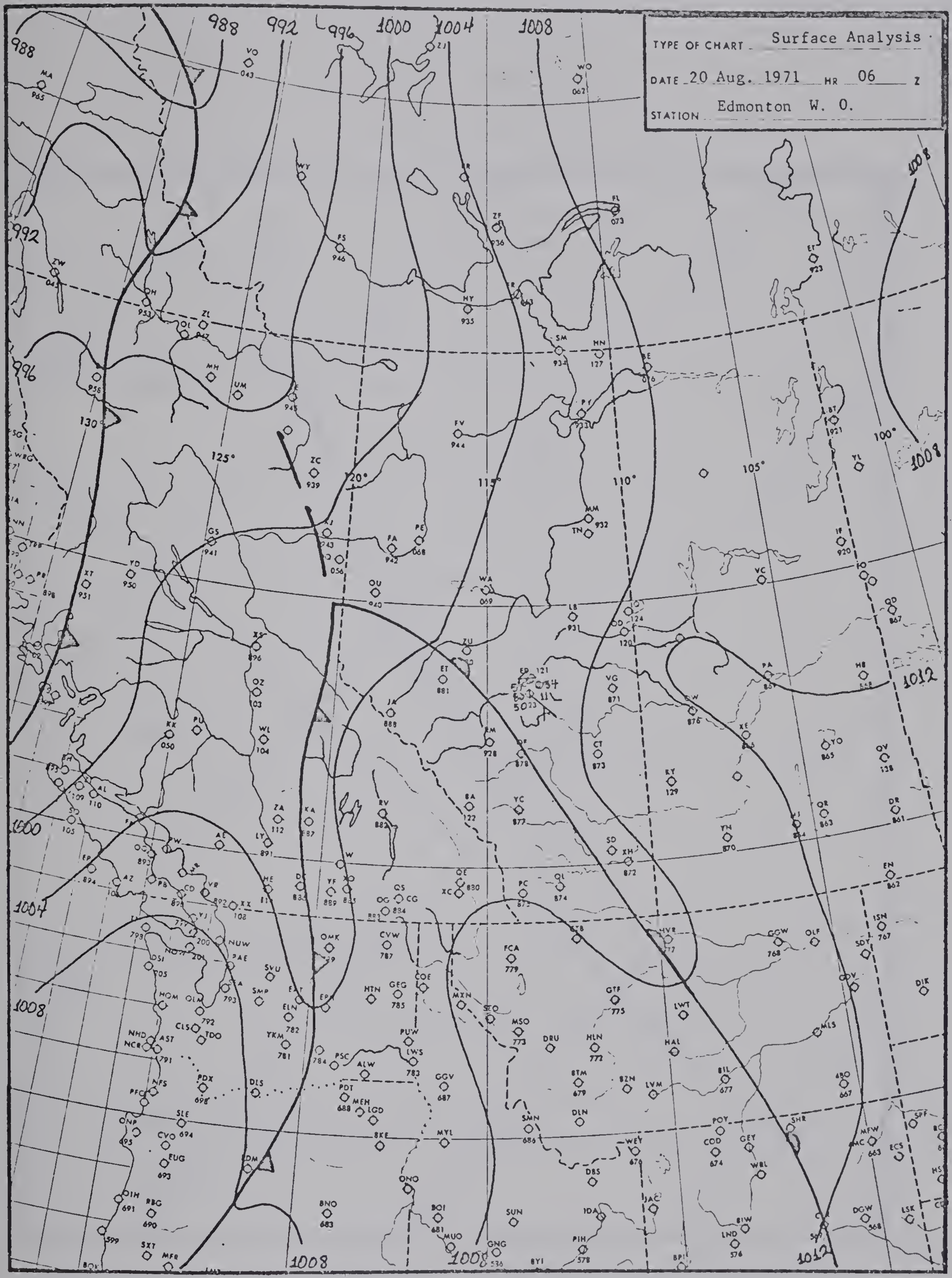

Figure 25. August 20, 1971, 0600 GMT Surface analysis.

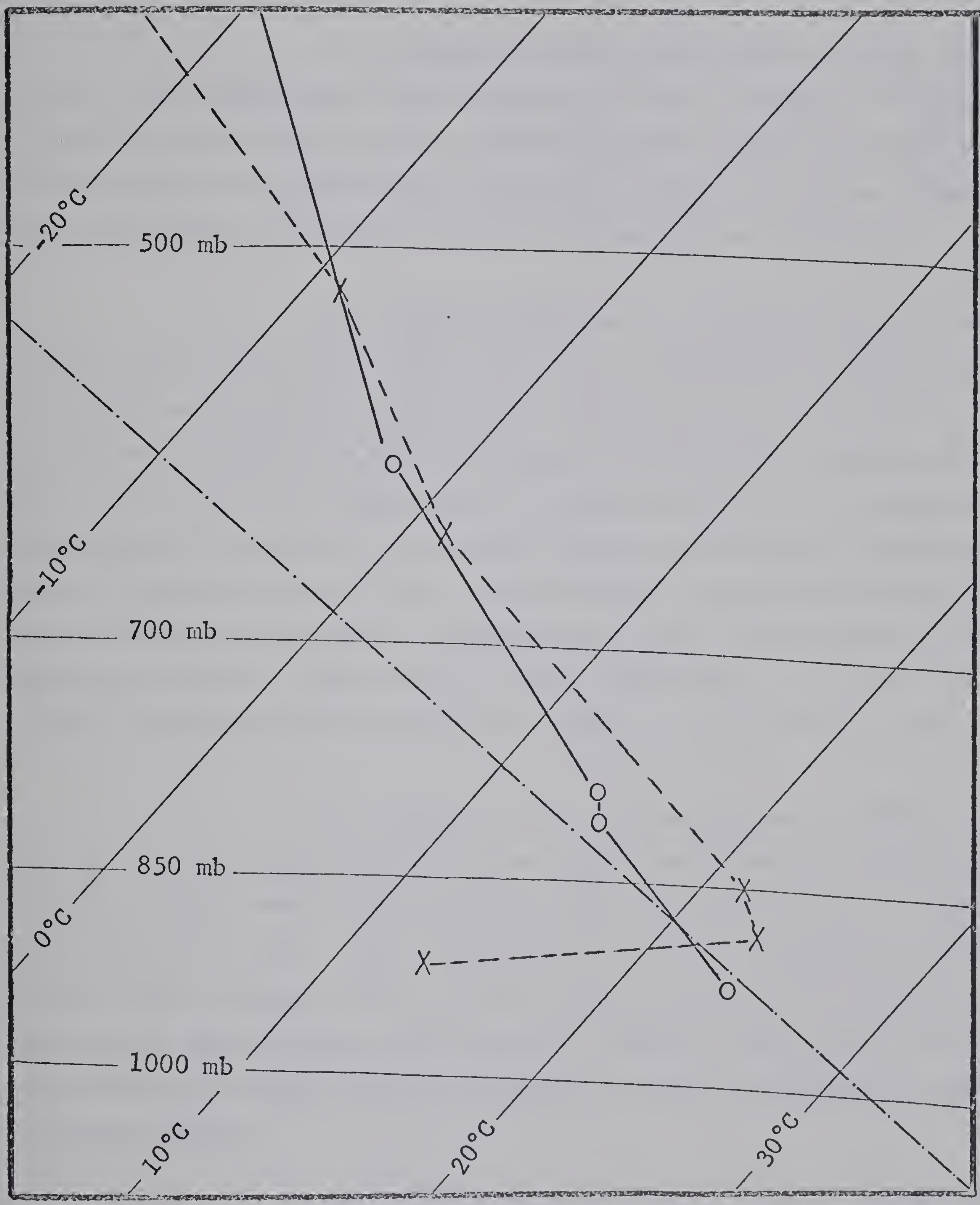

Figure 26. The Stony Plain tephigram for 20 August 1971.

——— 0000 GMT

------- 1200 GMT

surface inversion as was indicated by the 12 GMT sounding.

An inversion was also found over the city after sunset. The temperature data from the CN Tower as shown in Figures 27 and 28 indicated that the inversion became established shortly after sunset. The temperature difference reached a maximum value at 0800 GMT when an inversion of 1.7C°/100 meters was recorded.

The 0400 GMT temperature and wind analysis for the urban area (Figure 29) showed that a very strong heat island was in existence even shortly after sunset. The wind flow at all of the towers indicated a dominating easterly component (Table 14). Figures 30, 31, 32, and 33 show the temperature and wind analysis as the experiment progressed. The centre of the heat island was displaced slightly northwest of the main core of the city as would be expected with the flow out of the east-southeast. The generally light flow resulted in some drainage into the river valley of the cool country air as was indicated by the strong temperature gradient along the banks of the river.

The analysis of the perturbations in Table 14 gave one of the most significant results of the experiments. Notice that at several of the towers the strength of the perturbation was as great as the mean wind itself. Even though the mean wind was light the perturbations were stronger than they had been on some of the previous nights. This again substantiates the theory of Vukovich (1971) where the strongest horizontal winds would be encountered when the atmosphere over the city was stable.

Also notice in Table 14 that the direction of the perturbations for the four towers are almost colinear with the line joining the tower to the centre of the city. This is the result which the theory would lead us to expect when the mean wind is zero.

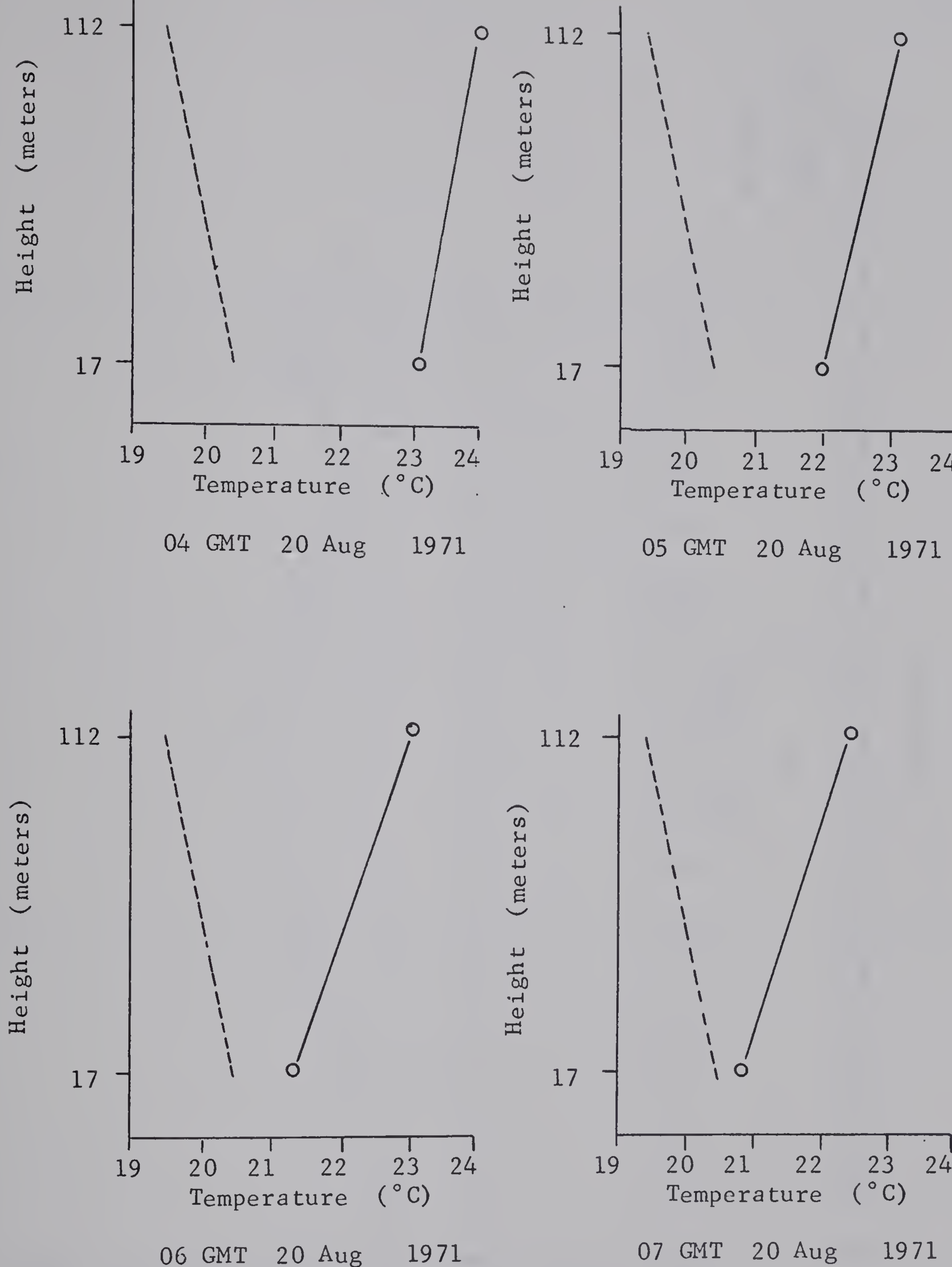

Figure 27. The CN Tower vertical temperature profiles.
----- dry adiabatic
——— CN Tower

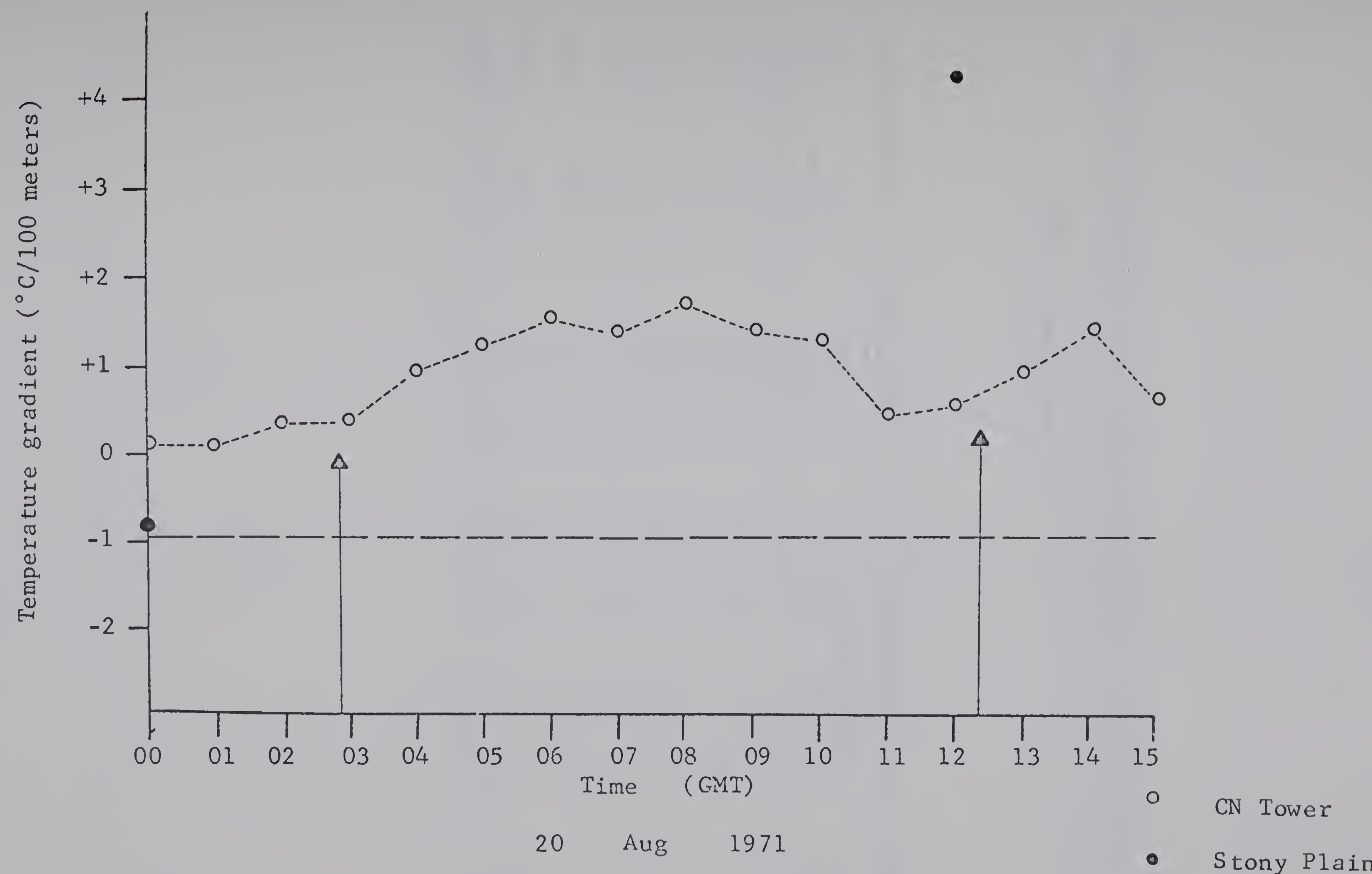

Figure 28. The vertical temperature gradient over the urban complex and the rural site.

(---- dry adiabatic)

TABLE 14. The half-hour average wind speed and direction, and the perturbation at each of the four towers. (Wind speeds m sec^{-1})

		Perturbation			
Time	Average	Tower #1	Tower #2	Tower #3	Tower #4
0400	103° 1.4	268° 0.4	165° 0.4	149° 0.5	64° 0.6
0430	111° 1.2	239° 0.4	162° 0.5	141° 0.4	50° 0.7
0500	117° 1.5	242° 0.7	188° 0.7	151° 0.4	38° 0.9
0530	123° 1.5	231° 0.8	196° 0.4	146° 1.0	14° 0.8
0600	130° 1.5	237° 1.0	222° 0.3	139° 1.4	9° 0.7
0630	141° 1.3	263° 0.5	180° 0.3	132° 1.4	335° 1.3
MEAN	121° 1.4	243° 0.6	177° 0.3	142° 0.8	25° 0.8

TABLE 15. Half-hour divergence (x10^{-5} sec^{-1}) values for the four Bellamy triangles.

Time	Triangle #1	Triangle #2	Triangle #3	Triangle #4
0400	- 8.7	-11.8	- 5.8	-18.0
0430	+ 6.2	- 6.0	-15.6	-24.9
0500	-12.1	-16.3	-21.2	-36.3
0530	-22.9	-22.7	-17.5	-30.2
0600	-32.0	-29.5	-18.4	-23.9
0630	-39.5	-32.3	-14.2	-32.2
MEAN	-18.2	-19.8	-15.4	-27.6

TABLE 16. Half-hour vorticity (x10^{-5}) values for the four Bellamy triangles. Positive values are counterclockwise.

Time	Triangle #1	Triangle #2	Triangle #3	Triangle #4
0400	+17.9	+ 8.5	+ 3.0	- 1.5
0430	+ 4.7	+12.9	+ 6.7	-17.7
0500	+ 6.6	+12.1	+10.5	- 3.5
0530	+17.3	+10.9	+ 8.3	+ 7.9
0600	+24.3	+10.8	+ 7.3	+22.3
0630	+16.4	- 4.4	- 6.8	+25.4
MEAN	+14.5	+ 8.5	+ 4.8	+ 5.5

Triangle #4 in Table 15 revealed that there was net horizontal convergence upwind of the city centre. Notice in this table that all of the triangles were showing net horizontal convergence throughout most of the night. The vorticity calculations in Table 16 are also quite interesting. Notice that the upwind Triangles #1 and #4 show some oscillation but that a net counterclockwise component is evident by the end of the experiment. On the other hand the downwind Triangles #2 and #3 started with a counterclockwise component but the strength of it gradually decreased so that there was a clockwise contribution by the end of the night.

In an attempt to observe the pulsating nature of the induced circulation such as has been theoretically postulated it was decided to calculate the divergence with a five minute averaging period. The results of these calculations are tabulated in Table 15a. It was interesting to note that at least some oscillation was observed with each of the four triangles. A necessary condition for the existence of a pulsating circulation is the oscillation of the intensity of the convergence. The magnitude of the oscillation found here is small. Keeping in mind the sensitivity of the divergence calculations as discussed in section 4.4 it was not possible to determine whether these oscillations were ordered or random.

TABLE 15a. Five-minute divergence (x10^{-5} sec^{-1}) values for the four Bellamy triangles for the half-hour period 0600 GMT to 0630 GMT, 20 August 1971.

Time	Triangle #1	Triangle #2	Triangle #3	Triangle #4
0600	-25.2	-28.8	-15.2	-18.2
0605	-28.7	-27.2	-13.5	-26.0
0610	-30.9	-27.9	-13.2	-27.9
0615	-39.9	-35.1	-13.7	-25.9
0620	-35.0	-33.0	-12.2	-28.7
0625	-33.8	-45.7	-39.1	- 9.3
0630	-27.6	-20.8	- 4.0	-28.7
MEAN	-31.6	-31.2	-15.8	-23.5

Figure 29. Wind and temperature distribution 0400 GMT, August 20, 1971. Isotherm spacing 2C°.

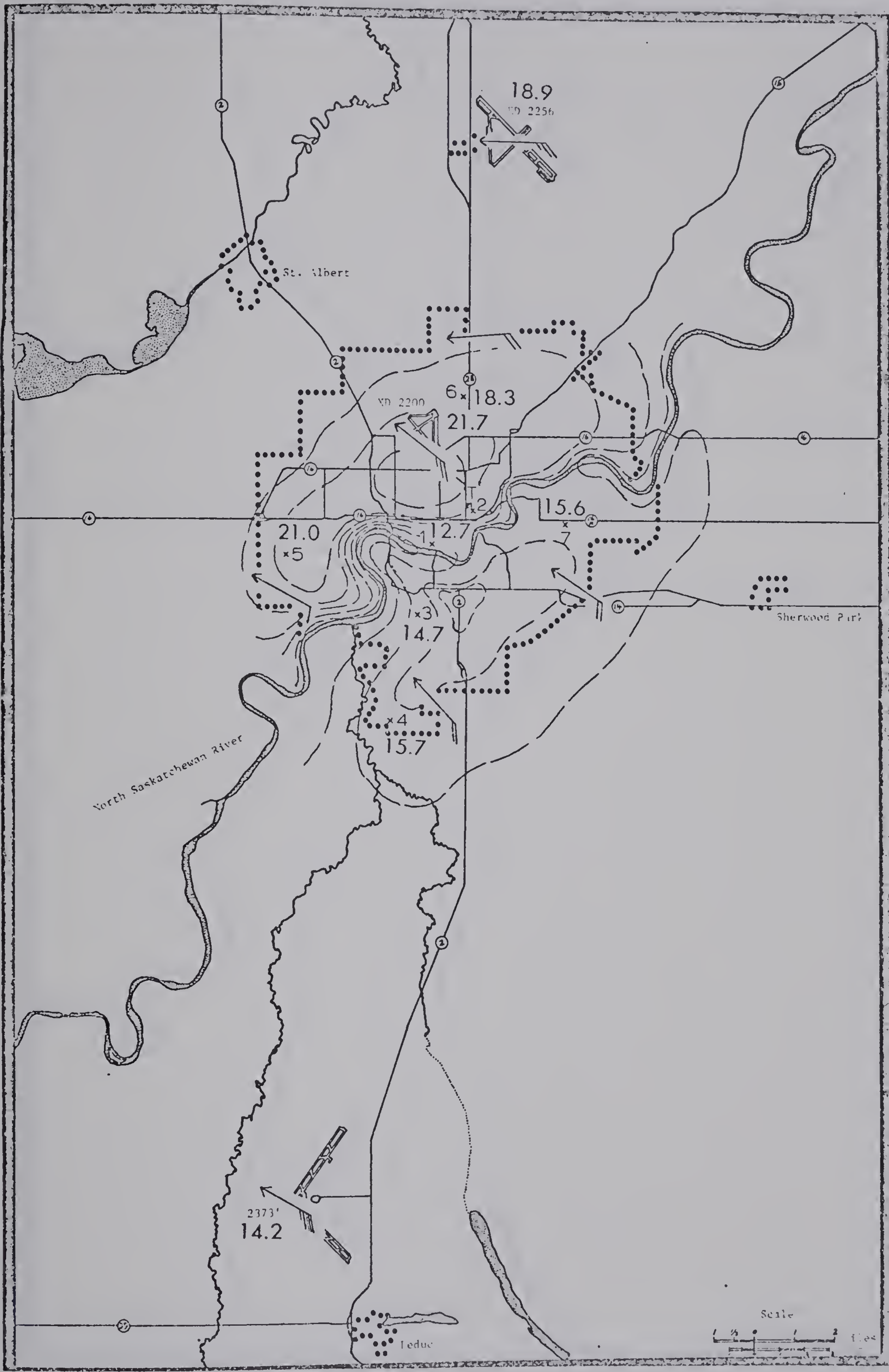

Figure 30. Wind and temperature distribution 0500 GMT, August 20, 1971. Isotherm distribution 2C°.

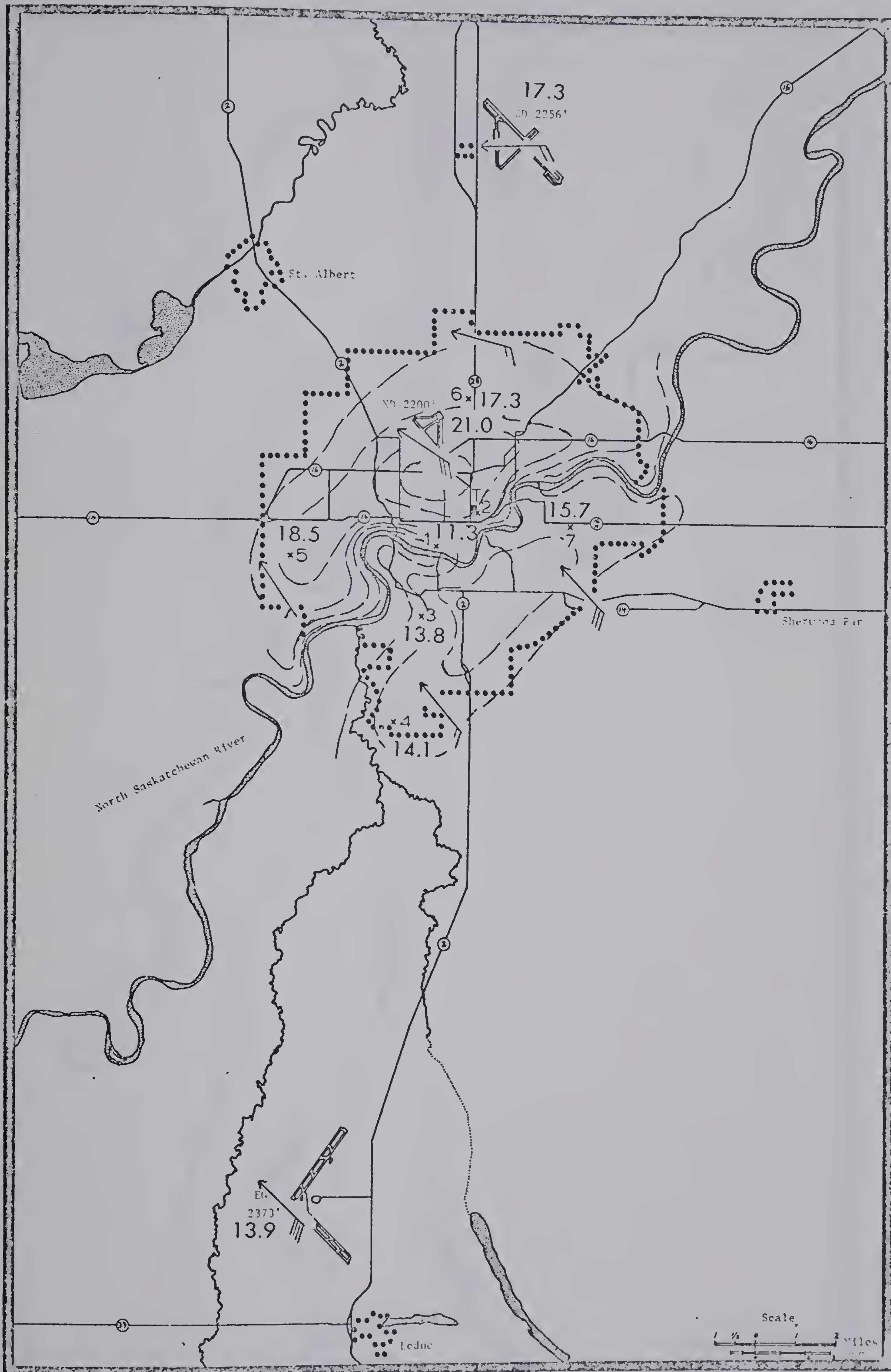

Figure 31. Wind and temperature distribution 0600 GMT, August 20, 1971. Isotherm distribution 2C°.

Figure 32. Wind and temperature distribution 0630 GMT, August 20, 1971. Isotherm spacing 2C°.

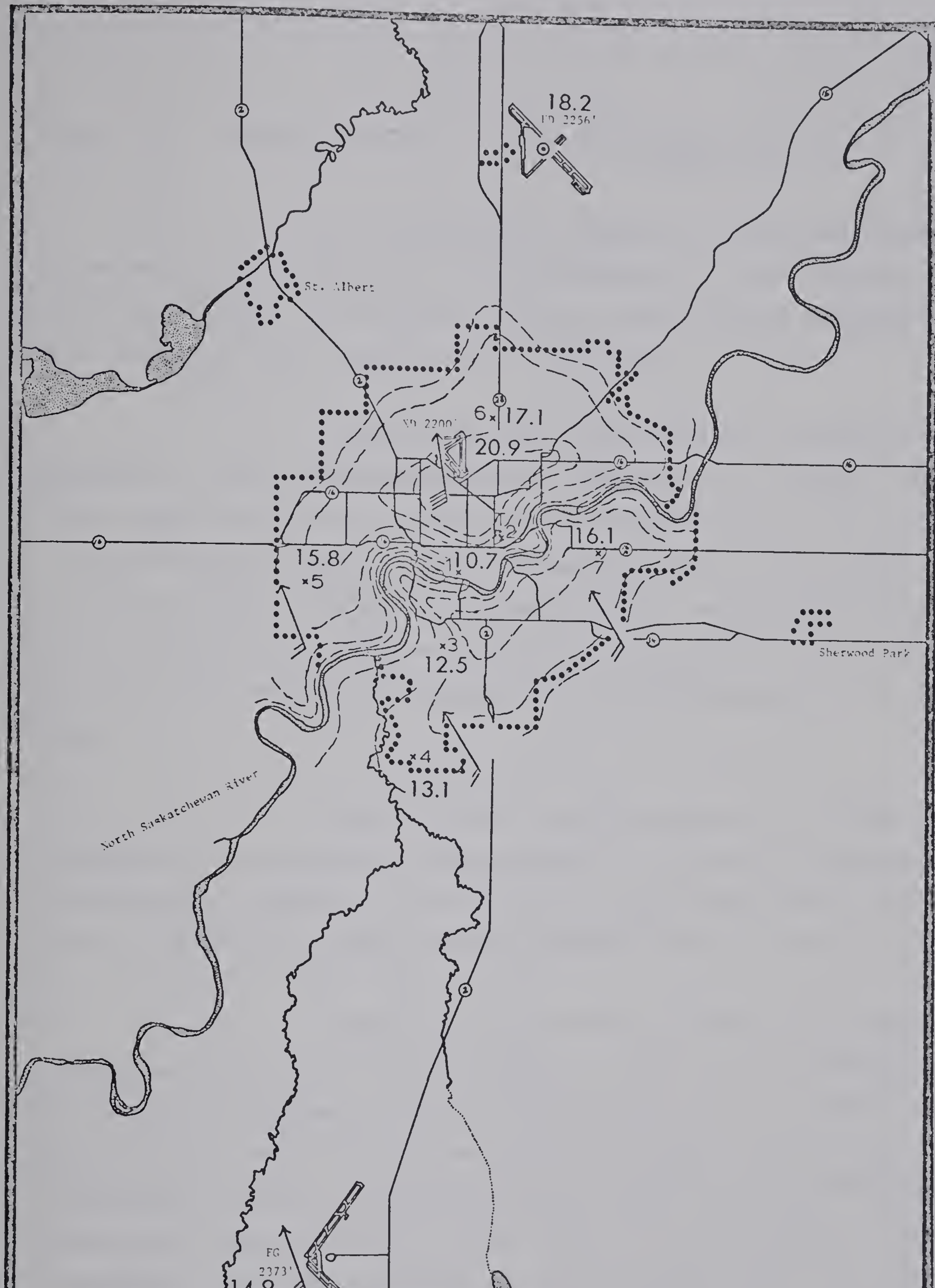

Figure 33. Wind and temperature distribution 0700 GMT, August 20, 1971. Isotherm spacing 2C°.

4.12 Experiment #7 18 September 1971

The greatest wind speeds were measured during Experiment #7 on the evening of 17 September 1971. The average of the hourly wind speed observations from the three Edmonton airports for the duration of the experiment was 4.9 m sec^{-1}.

The day had been fairly warm for the middle of September as the maximum temperature reached 16.7°C. However, nearly clear skies resulted in an overnight minimum temperature of -1.1°C giving widespread frost to the surrounding regions. The average wind for the day was 4.0 m sec^{-1}. The most frequent wind direction for the day was out of the S. The maximum wind for the day was out of the SSW at 8.0 m sec^{-1} which was recorded near the commencement of the experiment.

Figure 34, the surface analysis for 00 GMT, 18 September 1971, revealed a high pressure cell centred in northeast Montana and a deepening low pressure area near Snare River, NWT. This gave a moderately intense pressure gradient from the south to the north.

Figure 35, the 00 GMT and 12 GMT, 18 September 1971, tephigrams from Stony Plain were quite similar to the soundings from the previous experiments. The main differences were the lower temperatures at all levels in this early fall sounding. The character of the temperature profiles, however, remained similar. The 12 GMT tephigram showed that some warming had taken place in the mid levels of the atmosphere. The near dry adiabatic lapse profile found in the low levels at 00 GMT rapidly changed overnight to a sharp surface inversion.

The vertical temperature profile over the urban complex was quite different from the rural profile. Figures 36 and 37 which show the data from the CN Tower indicated that a near isothermal

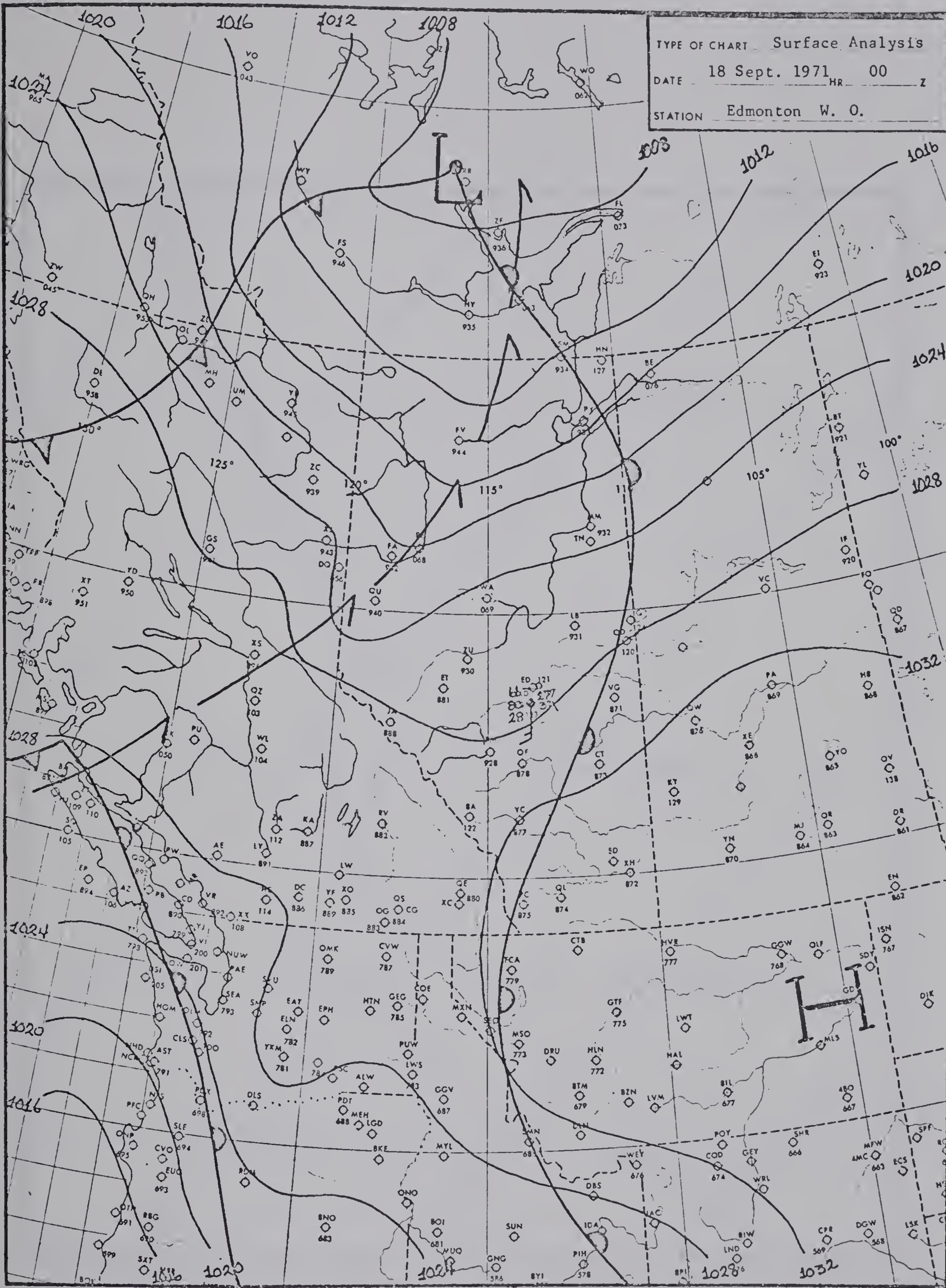

Figure 34. September 18, 1971, 0000 GMT Surface analysis

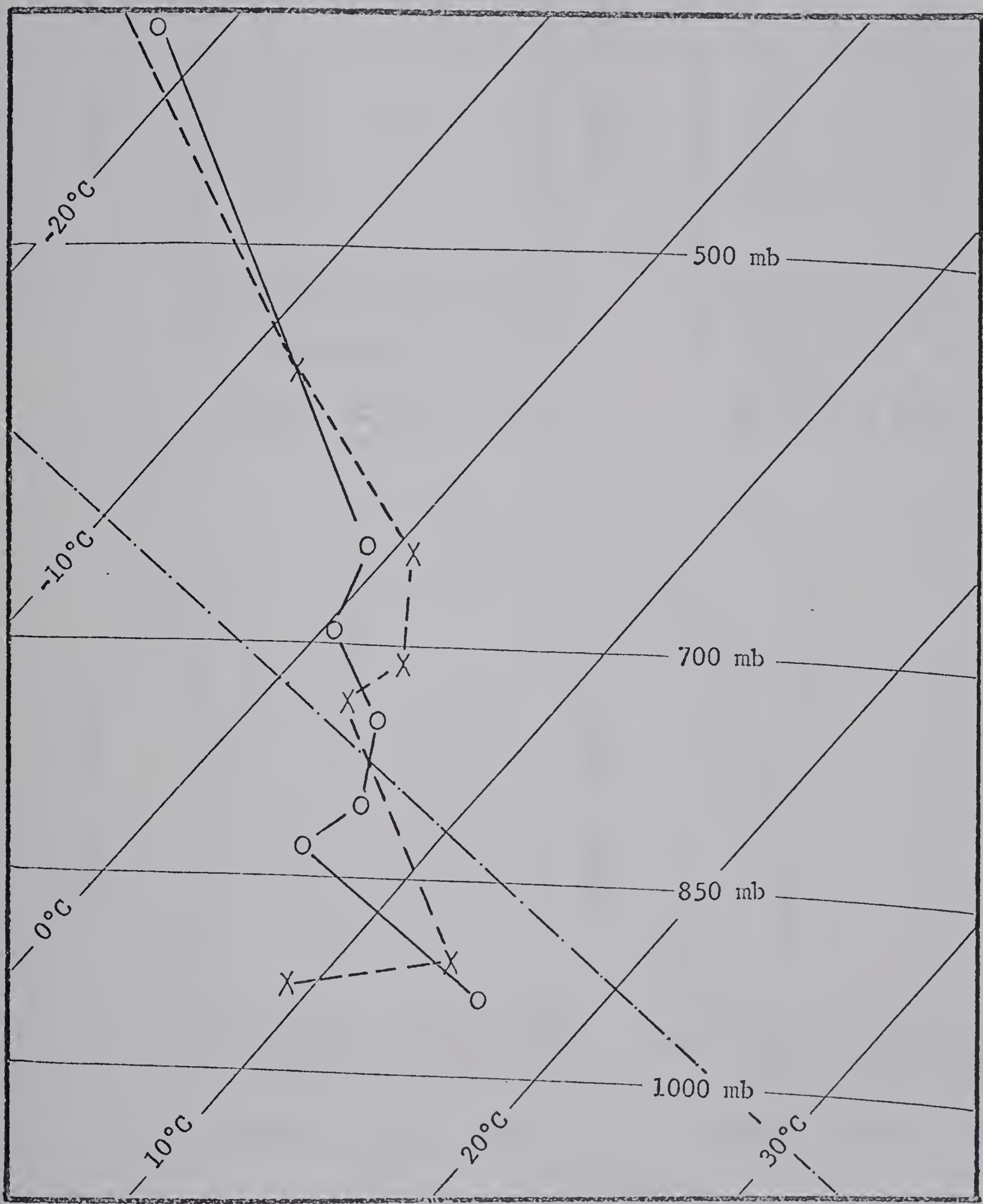

Figure 35. The Stony Plain tephigram for 18 September 1971.

——— 0000 GMT
----- 1200 GMT

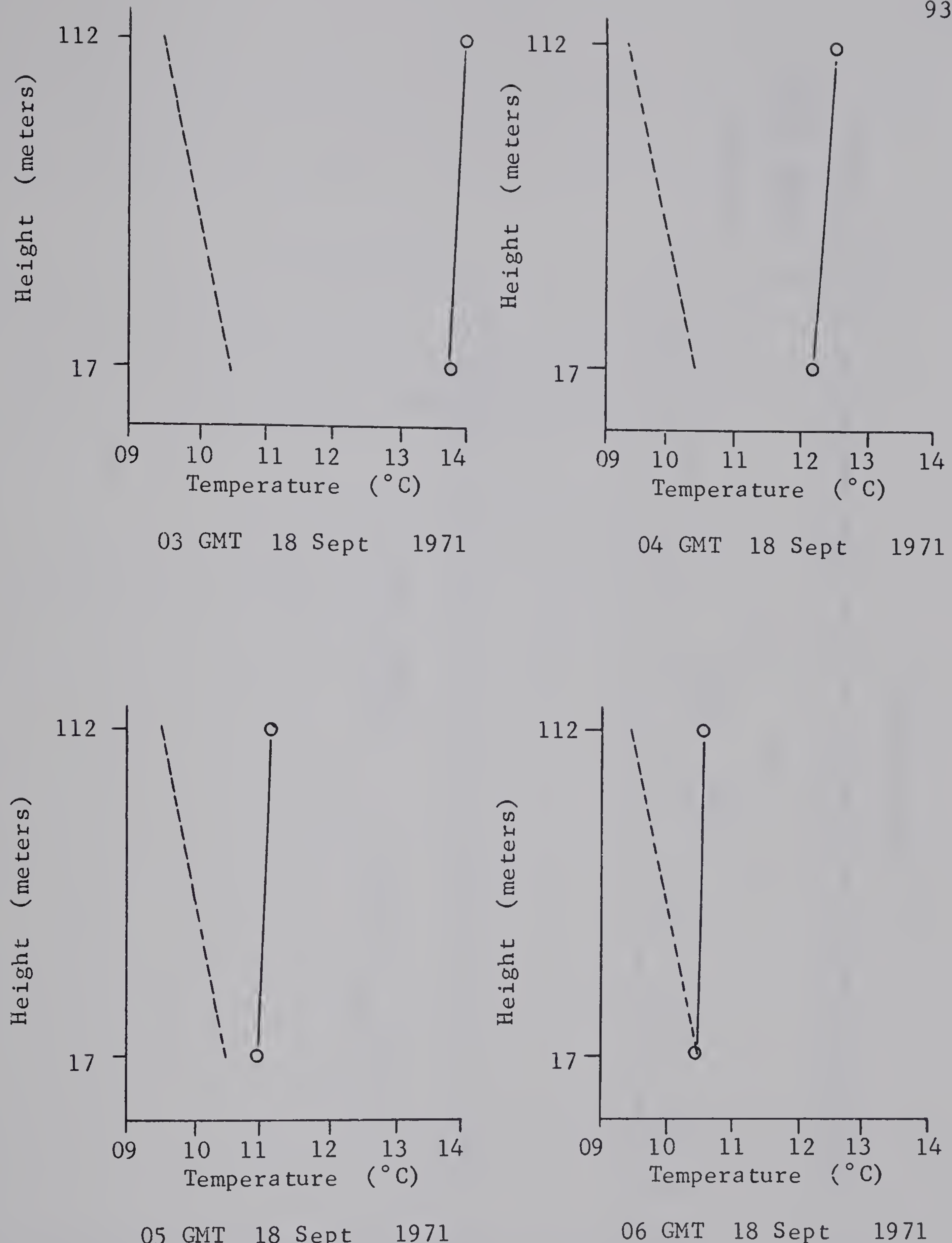

Figure 36. The CN Tower vertical temperature profiles.
----- dry adiabatic
——— CN Tower

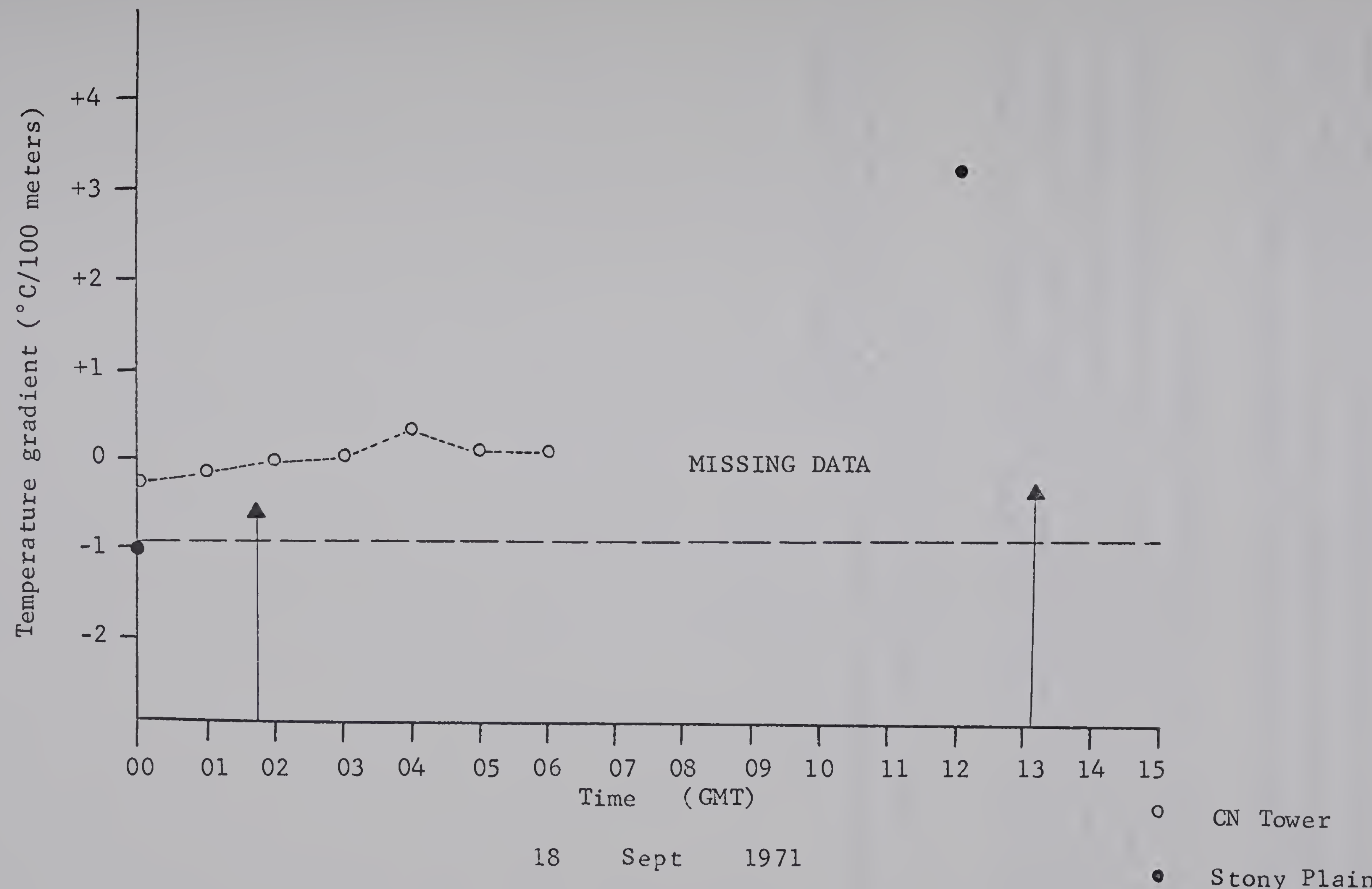

Figure 37. The vertical temperature gradient over the urban complex and the rural site.

(---- dry adiabatic)

temperature profile was characteristic of the city. The brisk surface winds and roughness of the city resulted in a greater degree of turbulence and hence more mixing of the air over the urban complex.

Although the winds were brisk, there was still net horizontal convergence upwind of the city centre as shown in Table 18. The downwind Triangles #2 and #3 on the other hand showed divergence throughout the night. This was a manifestation of the strong perturbations at the downwind site, Tower #4 as shown in Table 17.

The vorticity calculations in Table 19 indicated that upwind of the city centre there was a strong counterclockwise component of the vorticity.

TABLE 17. The half-hour average wind speed and direction, and the perturbation at each of the four towers (Wind speeds m sec^{-1})

Time	Average	Perturbation Tower #1	Tower #2	Tower #3	Tower #4
0230	178° 2.4	192° 0.8	91° 0.8	103° 0.5	231° 1.4
0300	178° 2.4	234° 0.4	112° 0.7	129° 0.8	223° 1.4
0330	175° 2.6	208° 0.9	113° 0.7	107° 0.6	224° 1.2
0400	177° 2.4	198° 1.1	128° 0.7	117° 0.6	211° 1.4
MEAN	177° 2.5	204° 0.8	110° 0.7	116° 0.6	222° 1.3

TABLE 18. Half-hour divergence ($\times 10^{-5}$ sec^{-1}) values for the four Bellamy triangles.

Time	Triangle #1	Triangle #2	Triangle #3	Triangle #4
0230	+ 0.6	+ 9.4	+ 2.3	-41.2
0300	- 0.0	+ 8.8	+ 3.8	-44.1
0330	- 1.0	+ 3.8	+ 0.7	-37.5
0400	+ 2.6	+ 8.6	+ 5.0	-25.9
MEAN	+ 0.5	+ 7.6	+ 2.9	-37.2

TABLE 19. Half-hour vorticity ($\times 10^{-5}$) values for the four Bellamy triangles. Positive values are counterclockwise.

Time	Triangle #1	Triangle #2	Triangle #3	Triangle #4
0230	-23.6	- 9.0	+ 1.8	+19.8
0300	-27.7	-15.7	- 5.7	+26.1
0330	-10.9	- 3.8	+ 1.4	+29.6
0400	- 7.1	+ 1.0	+ 7.3	+28.2
MEAN	-17.3	- 6.9	+ 1.2	+25.9

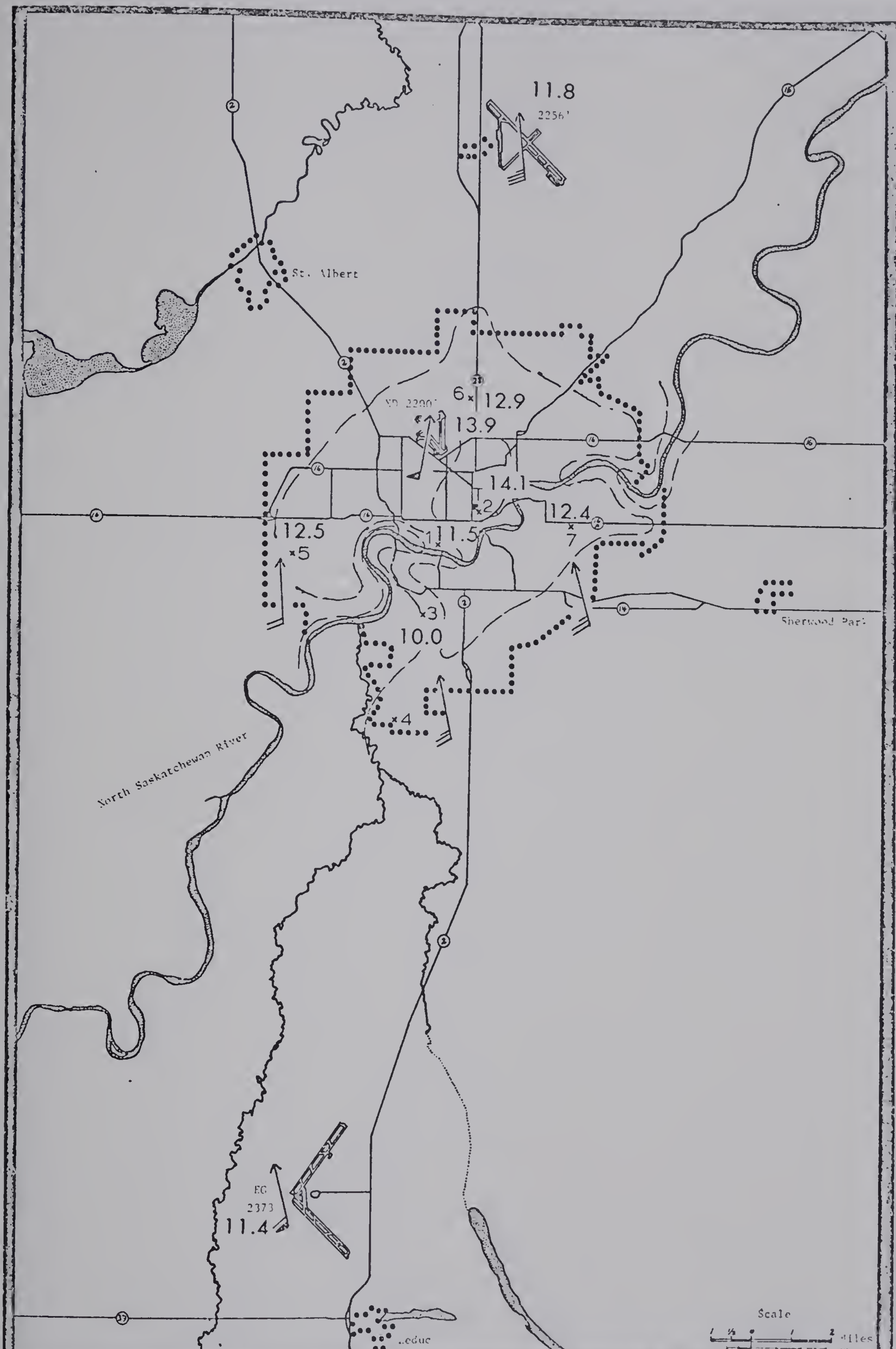

Figure 38. Wind and temperature distribution 0200 GMT, September 18, 1971. Isotherm spacing 2C°.

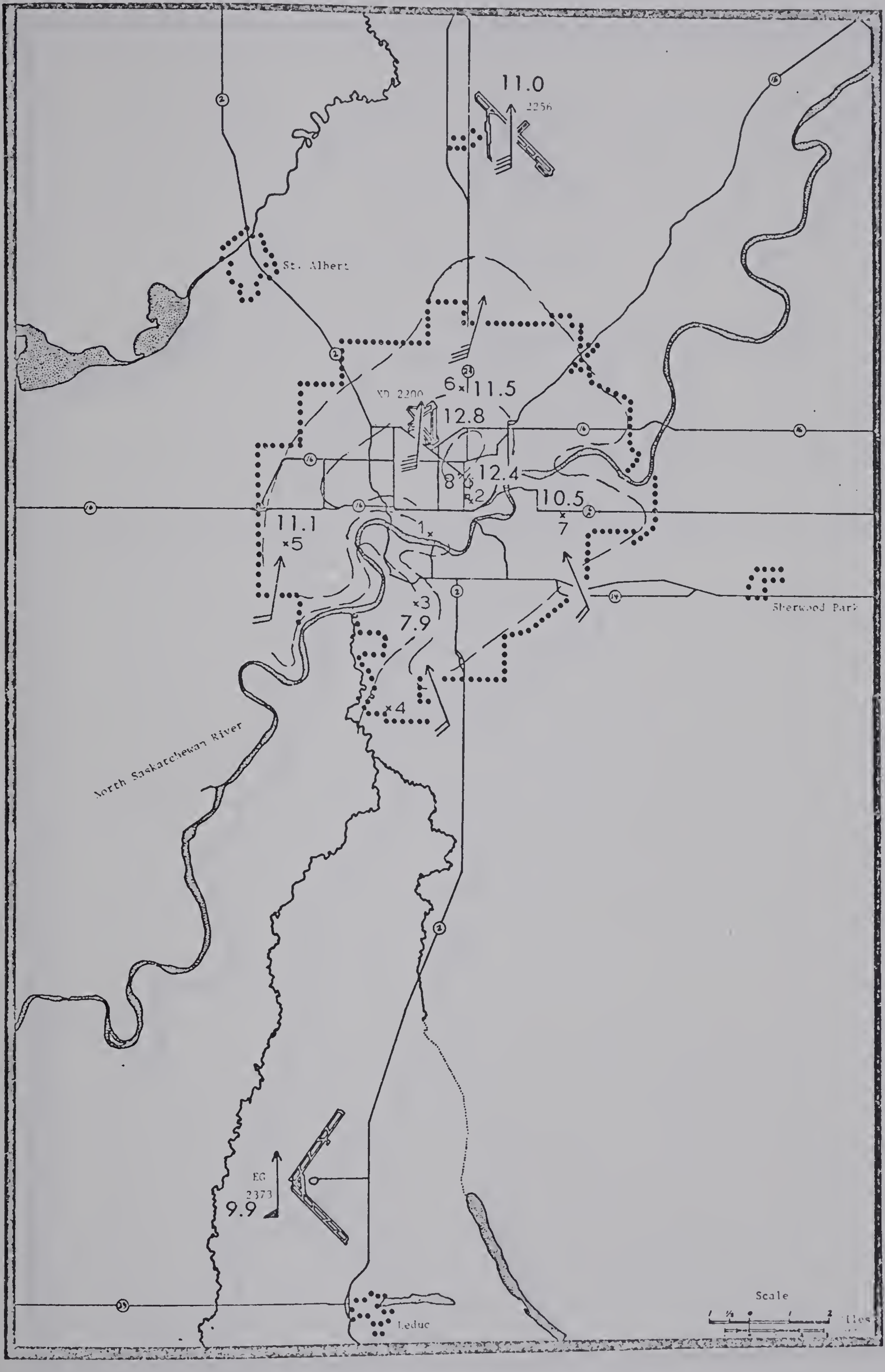

Figure 39. Wind and temperature distribution 0300 GMT, September 18, 1971. Isotherm spacing 2C°.

Figure 40. Wind and temperature distribution 0400 GMT, September 18, 1971. Isotherm spacing 2C°.

CHAPTER V

SUMMARY AND CONCLUSIONS

5.1 Summary and Conclusions to the Experiments

The aim of the experiments was to see if there was a meso-scale circulation induced by the heat island associated with the city of Edmonton. Such a circulation was predicted through theoretical considerations and such a circulation was measured during these experiments.

In all cases the synoptic weather pattern indicated an area of high pressure to the south or southeast of Edmonton with areas of lower pressure to the north. The pressure gradient was of varying intensity resulting in mean flows that ranged from very light (Experiment #6) to moderately strong (about 5.0 m sec^{-1} during Experiment #7). The opacity of the sky during the experiments was never greater than 2/10. In all cases the daily maximum temperatures were near normal or higher and the overnight temperatures dropped quite sharply from their daytime values.

The radiosonde data from Stony Plain were remarkably similar in character during all of the experiments. The lowest levels of the atmosphere indicated a near dry adiabatic lapse profile late in the day giving way to a sharp surface inversion overnight. In all cases significant warming had taken place in the mid levels of the atmosphere. These characteristics of the atmosphere were manifestations of the synoptic pattern which seemed to favor the induction of the meso-scale circulation. With higher pressures to the south of the region a south or southwest flow would be enhanced. During the summer months such a flow direction is indicative of warm air advection. Similarly

the influence of the high pressure cell is most often indicated through dry subsiding air and very few clouds. These conditions enhance strong surface radiation overnight allowing surface temperatures to plummet and a sharp inversion to form.

The urban vertical temperature profile varied in its nature from the near-neutral conditions which were found during Experiments #3 and #4 to the isothermal profile of Experiment #7 to the inversions encountered during Experiments #5 and #6.

The strongest horizontal perturbations were found during the experiments when the atmosphere over the city was stable. This was suggested by Vukovich (1971) in a theoretical consideration of the urban heat island circulation. The directions of the perturbations were to a certain extent colinear with the line which joined the tower to the centre of the city. The perturbation winds particularly at the downwind site were quite sensitive to the mean wind speed. A slight fluctuation in the speed of the mean wind was often enough to change the perturbation at the downwind site by 180°.

In all cases there was net horizontal convergence upwind of the city centre. There was some variation of the intensity of the convergence from night to night. There was also some apparent oscillation of the intensity during the night. This was best shown during Experiment #6 where five-minute averages of the convergence were calculated. A necessary result of a pulsating circulation is an

Downwind of the city centre there was convergence when the mean flow was light and divergence when the mean flow increased in intensity. Experiment #7 when the strongest mean flow was encountered saw net horizontal divergence downwind of the city centre throughout the night.

The vorticity calculations were quite interesting. A counterclockwise contribution to the vertical component of the vorticity was found in the upwind triangle in all cases. The downwind contribution was not as easily discernable.

5.2 Qualifications

The results of the calculations of the perturbation, convergence, and vorticity made in this study of urban circulation are quite significant. However, some word of qualification is in order. In sections 4.4, 4.5, and 4.6 the limitations of the instruments, the drainage effects near the sites, and the sensitivity of the vorticity and divergence calculations were examined. It was shown that there were no major systematic errors in the instruments, the drainage effects were more or less similar at all four sites, and the divergence and vorticity calculations could tolerate wind direction errors in the order of 10° and wind speed errors in the order of 20 cm sec^{-1} without significant variation of the calculations.

There are still two tests which could be made to make these results even more conclusive. Perhaps there were errors in wind due to local exposure problems. As was described in the last sections of Chapter 3, all of the experimental sites were open and flat. This does not, however, preclude some systematic error due to the exposure of the tower, at one of the sites. If similar results could be obtained at different sites than the ones used, these results would be that much more conclusive.

Perhaps the convergence and vorticity patterns would have been the same with no heat island. Unfortunately there was no experiment conducted when there was no heat island. Figure 41 is a scatter diagram of convergence intensity (as determined by Triangle #4)

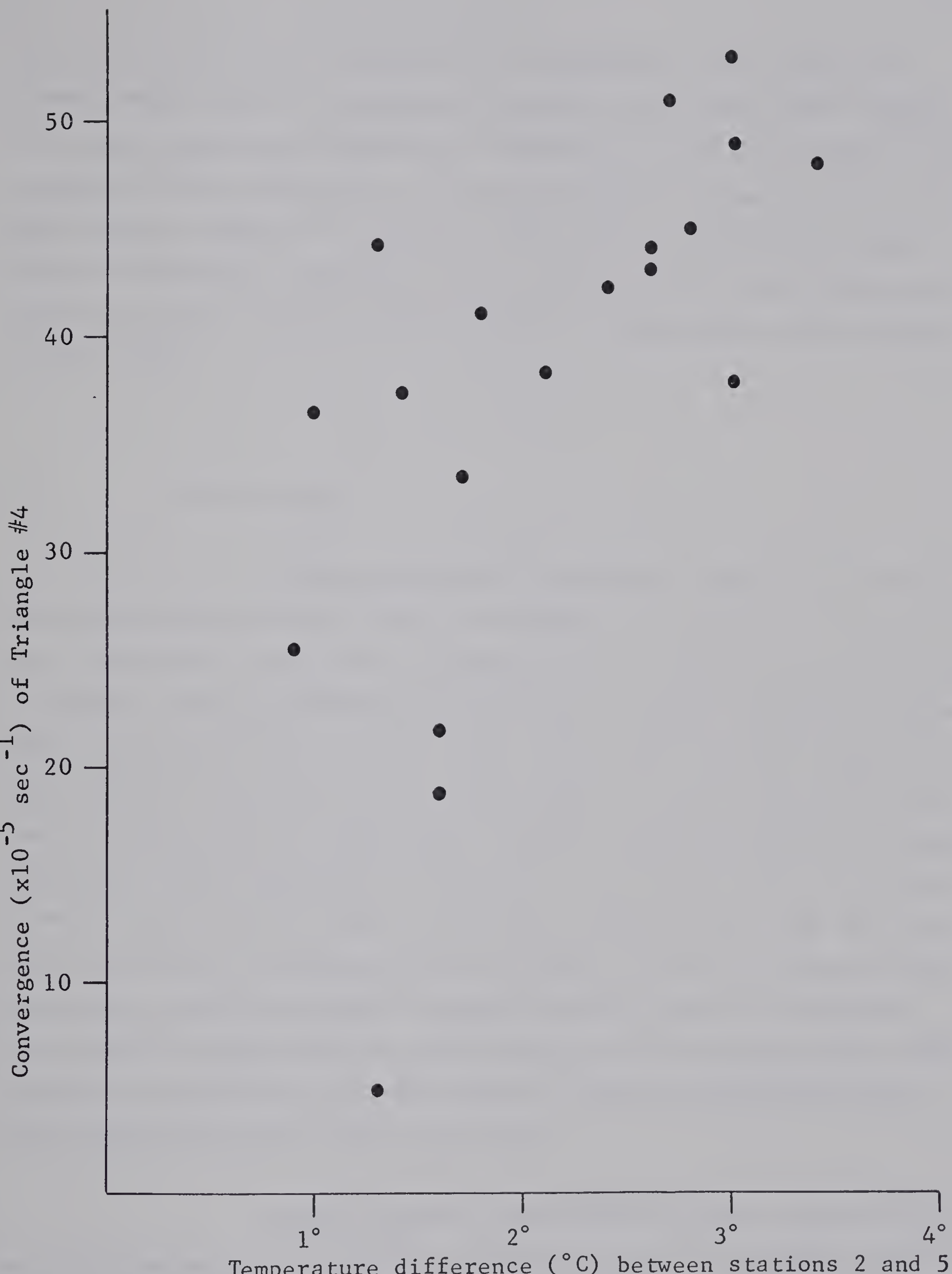

Figure 41. Scatter diagram of convergence intensity versus heat island intensity.

versus the heat island intensity (as determined by the difference between temperatures at stations #5 and #2). Note that there appears to be some correlation between the intensity of the heat island and the strength of the convergence. If the perturbations superimposed on the mean flow are induced by the heat island then the correlation must follow. Experiments conducted during conditions when there was no heat island would give results against which to compare the results found in this study.

5.3 Implications

There are several significant implications which follow from the results of these experiments. The first has to do with urban ventilation. Under the no-mean-wind case the circulation induced by the heat island of Edmonton would tend to aid the removal of atmospheric pollutants from the core area: the vertical updraft over the centre of the city would help in this respect. On the other hand the case of no mean wind is very rare. The data from the Industrial Airport indicated "calm" conditions on only 1% of the time. In all of the experiments conducted here there was always some mean wind and there was always convergence upwind of the city centre. Since the centre of the solenoidal circulation would be moved downwind from the core area, there would be convergence in the vicinity of the core area and rather than aid the ventilation of the city the induced circulation would carry pollutants towards the city centre.

Under synoptic conditions that were favourable for the continuation of the induced circulation over an extended period of time, this movement of pollutants towards the centre of the city would aid in yet a further complication. The increased pollution in the core area would add to the development of a strong heat island which in turn would increase the intensity of the solenoidal circulation.

5.4 Areas of Further Research

There have been only two other attempts to measure the urban induced circulation through Eulerian techniques. The results of Pooler (1963) had the difficulty of a wind shadow effect and Findlay and Hirt (1969) had the proximity of Lake Ontario to contend with. Thus one of the very important conclusions of these experiments is that the induced circulation can be inferred through Eulerian techniques. However, even further refinement of the equipment would make the results even more readily discernable.

First of all more tests are required to evaluate instrument and data abstraction errors. Also tests to check for drainage and exposure problems would be useful.

Secondly, additional towers could be placed in the northwest and northeast areas of the city so that a finer structure could be extracted. Thirdly, if the observations could be read directly onto magnetic tape a finer timewise integration of the flow would be possible. This would be especially interesting for the attempt to observe the pulsating nature of the flow.

An interesting extension of the experiment would be into the third dimension. This would involve the use of three dimensional vanes not only around the edge of the city but around the core area as well. These towers would be instrumented with the vanes at several levels.

This type of analysis would give a good three dimensional structure picture to the urban induced meso-scale circulation. Such a detailed structure is needed to improve the models of urban diffusion. Such detailed structure is of paramount importance to set about the understanding of the complex question of urban ventilation. Hopefully this thesis is one small step in that direction.

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APPENDIX A

THE SUMMER OF 1971 COMPARED TO CLIMATIC AVERAGES

A-1 June 1971

The mean daily temperature for the month of June was slightly above normal. However the above normal cloud amounts kept the mean daily maximums 1.1C° below normal and the mean daily minimums 1.1C° above normal to obtain this balanced mean.

Precipitation for the month totalled 9.75 cm which is one-third more than normal. Measureable precipitation occurred on 15 days during the month and a trace or more on 20 days. Sunshine totalled 214.6 hours which was the lowest June total since 1954.

A-2 July 1971

During the first thirteen days of July the weather continued cloudy and cool. In that space of time 9.14 cm of rain fell which exceeded the month's long term average of 8.33 cm. There were 15 days of measureable precipitation and six days with thunderstorms.

The highest maximum temperature was 29.8°C and the minimum was 6.0°C. The mean monthly temperature was 16.8°C, 0.6C° below the July normal.

The month also proved to be quite windy with a mean speed of 4.9 m sec^{-1} which exceeded the July normal of 4.4 m sec^{-1}.

A-3 August 1971

The mean daily temperature for August in the city of Edmonton was 21.6°C which was the highest on record since observations began in 1880. The previously high daily mean for August was 21.2°C, recorded in 1967. The previous monthly high was set in July 1960 with a daily mean of 21.3°C.

Maximum temperatures of 26.5°C or higher were recorded on 14 days. Average daily maximum temperature was 25.2°C, 3.5C° above the long term normal. Average daily minimum temperature was 13.5°C, again 3.5C° above normal and the highest daily mean minimum of any month on record.

The warm air which covered the city during the first 11 days of the month was moist and produced five thunderstorms on consecutive days from the third to the seventh but produced little precipitation. Measureable rain fell on only four days for a total of 1.19 cm, 17% of normal. This was the fourth driest August on record.

A-4 September 1971

The mean temperature for Edmonton for the month of September was 10.2°C, 0.7C° below normal. This deficit was all on the maximum temperature side as maximums averaged 1.5C° below normal while the minimums averaged slightly above normal.

The first frost of the season occurred on the night of September 17th, the same day as Experiment #7 was conducted.

A storm on September 29th and 30th dumped 7.62 cm of wet snow on the city. However it melted as it landed. Total snowfall was 7.62 cm. Total precipitation was 2.26 cm, 62% of normal.

September 1971 was the windiest September ever on record at Edmonton with a mean speed for the month of 5.5 m sec^{-1}.

A-5 Climatic Tables

The following tables are given for a comparison of the summer of 1971 to the climatic normals for the same period. In Tables A-2, A-4, A-6, and A-8 the wind speeds are coded as ranges. These ranges are:

Range 1	0.5 to 1.5 m sec^{-1}
Range 2	2.0 to 3.5 m sec^{-1}
Range 3	4.0 to 6.0 m sec^{-1}
Range 4	6.5 to 9.0 m sec^{-1}
Range 5	9.5 to 12.0 m sec^{-1}
Range 6	12.5 to 15.5 m sec^{-1}
Range 7	16.0 to 19.0 m sec^{-1}
Range 8	19.5 to 23.0 m sec^{-1}

In Tables A-1, A-3, A-5, and A-7 the end column "No. TRW" is the number of thunderstorms.

TABLE A-1. A comparison of the month of June 1971 to the climatic normals for June based on the period 1941 - 1970.

	Temperature(°C) max	min	mean	Total Precip	Total hrs. bright sun	Average wind	Prevailing direction	No. TRW
1971	19.4	10.1	14.8	9.75 cm	214.6	5.2 m sec^{-1}	WNW	7
Norm	20.5	8.9	14.6	7 47 cm	251.2	5.0 m sec^{-1}	WNW, NW	4.4

TABLE A-2. June mean monthly wind speed frequency for the period 1957 - 1966.

RANGE	1	2	3	4	5	6	7	8	TOTAL	MEAN SPEED
Calm									13.3	
NNE	3.1	9.8	9.9	8.3	1.5				32.6	4.8
NE	4.2	14.7	17.9	7.8	2 3	0.1			47.0	4.7
ENE	1.7	10.5	15.6	5.4	1.5	0.5			35.2	4.8
E	3.4	14.0	11.4	5.7	0.7	0.1			35.3	4.2
ESE	1.5	8.1	14.8	7.5	1.1				33.0	5.0
SE	2.8	9.9	13.7	8.5	2.1	0.1			37.1	5.0
SSE	3.3	11.2	20.2	12.3	2.2	0.4			49.6	5.2
S	4.9	21.3	18.3	7.1	0.5	0.1			52.2	4.1
SSW	3.0	16.1	11.0	3.3	0.7				34.1	3.8
SW	3.7	14.4	7.3	0.9	0.3	0.2			26.8	3.3
WSW	2.2	11.2	12.8	3.0	1.2	0.8	0.4		31.6	4.6
W	3.4	15.6	21.0	9.4	3.2	0.9	0.2		53.7	5.0
WNW	2.8	14.7	25.8	21.9	6.9	0.6	0.3	0.1	73.1	5.9
NW	2.9	13.6	25.2	17.6	5.6	1.4	0.1		66.4	5.7
NNW	1.2	9.2	19.4	13.8	4.6	1.4	0.6	0.1	50.3	6.2
N	3.6	11.5	16.0	12.8	3.1	1.4	0.3		48.7	5.5
TOTAL	47.7	205.8	260.3	145.3	37.5	8.0	1.9	0.2	720.0	4.9

TABLE A-3. A comparison of the month of July 1971 to the climatic normals for July based on the period 1941 - 1970.

	Temperature(°C) max	min	mean	Total Precip	Total hrs. bright sun	Average wind	Prevailing direction	No. TRW
1971	21.6	11.9	16.8	12.7 cm	304.2	4.9 m sec^{-1}	WNW	6
Norm	23 4	11.5	17.4	8.3 cm	305.2	4.5 m sec^{-1}	WNW	8.5

TABLE A-4. July mean monthly wind speed frequency for the period 1957 - 1966.

RANGE	1	2	3	4	5	6	7	8	TOTAL	MEAN SPEED
Calm									15.2	
NNE	3.1	7.8	9.2	4.9	0.8				25.8	4.5
NE	2.9	12.2	10.2	4.9	0.2	0.3			30.2	4.1
ENE	3.2	10.4	10.0	4.2	0.3				28.1	4.1
E	4.3	8 1	13.8	5.3	0.6				32.1	4.4
ESE	1.5	7.8	10.7	5.7	0.5				26.2	4.7
SE	2.4	8.3	11.4	7.1	2.1	0.3			31.6	5.2
SSE	1.8	11.4	16.6	9.7	0.9	0.2			40.6	4.9
S	7.0	24.4	16.9	3.7	0.3				52.3	3.5
SSW	5.4	24.3	11.2	1.0	0.1	0.1			42.1	3.1
SW	4.6	25.8	12.5	1.6					44.5	3.2
WSW	3.1	17.6	14.6	3.7	0.3	0.3			39.6	3.9
W	5.3	22.7	30.0	13.0	2.1	0.4			73.5	4.6
WNW	4.8	19.9	34.0	26.2	4.5	1.0	0.1		90.5	5.4
NW	3.1	18.3	32.3	18.5	3.2	1.3	0.1		76.8	5.2
NNW	2.4	10.8	20.5	12.5	1.8	0.2	0.2		48.4	5.2
N	4.6	14.5	15.4	8.6	2.7	0.6	0.1		46.5	4.8
TOTAL	59.5	244.3	269.3	130.1	20.4	4.7	0.5		744.0	4.4

TABLE A-5. A comparison of the month of August 1971 to the climatic normals for August based on the period 1941 - 1970.

	Temperature(°C) max	min	mean	Total Precip	Total hrs. bright sun	Average wind	Prevailing direction	No. TRW
1971	25.2	13.5	19.4	1.19 cm	317.3	4.7 m sec^{-1}	S	5
Norm	21.8	10.1	15.9	7.16 cm	268.5	4.4 m sec^{-1}	S, WNW	5.7

TABLE A-6. August mean monthly wind speed frequency for the period 1957 - 1966.

RANGE	1	2	3	4	5	6	7	8	TOTAL	MEAN SPEED
Calm									18.7	
NNE	3.1	6.2	8.7	1.1					23.6	4.5
NE	3.6	9.4	9.3	4.2	0.7	0.1			27.3	4.2
ENE	2.3	6.0	10.1	1.9	0.7				21.0	4.3
E	4.5	10.0	10.8	4.7	0.6				30.6	4.0
ESE	1.8	7.1	8.6	5.5	0.8	0.1			23.9	4.7
SE	3.5	12.8	13.6	4.8	1.1	0.2			36.0	4.3
SSE	3.5	14.5	17.0	8.7	0.7	0.4			44.8	4.6
S	9.4	39.6	25.3	6.4	0.9				81.6	3.5
SSW	5.5	27.7	14.6	1.4					49.2	3.2
SW	7.0	26.5	12.1	1.1		0.1	0.1		46.9	3.1
WSW	2.5	15.3	14.4	2.7	0.3				35.2	3.9
W	5.6	23.3	28.8	10.9	2.4	0.9		0.1	72.0	4.6
WNW	3.5	17.9	34.7	19.8	4.4	1.6	0.3		82.2	5.4
NW	5.3	17.5	29.0	16.1	4.6	1.2	0.1	0.1	73.9	5.2
NNW	2.6	10.0	14.3	11.6	1.9	0.5		0.1	41.0	5.3
N	3.6	10.3	14.3	6.2	1.5	0.2			36.1	4.6
TOTAL	67.3	254.1	265.6	110.5	21.7	5.3	0.5	0.3	744.0	4.3

TABLE A-7. A comparison of the month of September 1971 to the climatic normals for September based on the period 1941 - 1970.

	Temperature(°C) max	min	mean	Total Precip	Total hrs. bright sun	Average wind	Prevailing direction	No. TRW
1971	15.2	5.2	10.2	2.26 cm	160.6	5.5 m sec^{-1}	WNW	0
Norm	16.8	5.0	10.9	3.60 cm	186.3	4.9 m sec^{-1}	S	1.1

TABLE A-8. September mean monthly wind speed frequency for the period 1957 - 1966.

RANGE	1	2	3	4	5	6	7	8	TOTAL	MEAN SPEED
Calm									13.8	
NNE	1.4	6.0	7.2	4.7	1.1	0.2			20.6	5.1
NE	3.7	7.6	9.8	2.1	1.3	0.1			24.6	4.2
ENE	1.0	5.2	9.1	1.9	0.3				17.5	4.5
E	2.3	6.8	7.1	3.2	0.6				20.0	4.3
ESE	1.2	5.1	7.0	5.6	1.3				20.2	5.2
SE	2.4	8.6	10.9	6.9	1.6	0.1			30.5	4.9
SSE	1.9	13.6	21 5	17.5	2.6				57.1	5.3
S	7.4	39.0	30.3	10.0	0.5				87.2	3.9
SSW	3.5	28.1	15.9	1.9					49.4	3.3
SW	5.2	27.0	12.0	2.3					46.5	3.3
WSW	2.5	14.8	10.9	2.3	0.1				30.6	3.6
W	4.4	19.5	22.0	6.1	2.6	0.5			55.1	4.4
WNW	2.5	11.1	25.4	17.2	6.3	1.6	0.2		64.3	6.0
NW	4.7	16.2	26.1	19.7	7.4	2.0	0.1		76.2	5.8
NNW	0.9	6.1	16.4	19.9	8.1	3.1	0.2		54.7	7.1
N	3.3	12.3	15.2	12.3	6.1	2.0	0.4	0.1	51.7	5.9
TOTAL	48.3	227.0	246.8	133.6	39.9	9.6	0.9	0.1	720.0	4.8